

1988

Finite-Rate Water Condensation in Combustion-Heated Wind Tunnels

Wayne D. Erickson
*Langley Research Center
Hampton, Virginia*

Gerald H. Mall
*Computer Sciences Corporation
Hampton, Virginia*

Ramadas K. Prabhu
*PRC Systems Services
A Division of Planning Research Corporation
Hampton, Virginia*

11.11.11

11.11.11

11.11.11

11.11.11

11.11.11

11.11.11

11.11.11



Symbols

A	nozzle cross-sectional area, m^2
$A_{n,k}$	constant coefficients in equation (36) for $C_{p,k}$
$a_{2,C}$	initial approximation of mols of CO_2 per total mol equivalence of C in mixture
$B_{n,j}$	constant coefficients in equation (35) for $K_{p,j}$
$C_{p,k}$	molar heat capacity of species k , J/mol-K
$c_{p,c}$	specific heat capacity of carrier gas, J/kg-K
$c_{p,k}$	specific heat capacity of species k , J/kg-K
$D_{n,k}$	constant coefficients in equation (63) for μ_k
$E_{n,k}$	constant coefficients in equation (66) for λ_k
F	function defined by equation (111)
f	factor to account for carrier gas defined by equation (74)
G	function defined by equation (46)
h	specific enthalpy of total mixture, J/kg
h_G	specific enthalpy of gaseous mixture, J/kg
h_L	specific enthalpy of liquid water, J/kg
h_o	stagnation specific enthalpy, J/kg
$\hat{h}_F, \hat{h}_{O_2}, \hat{h}_{N_2}$	specific enthalpy of fuel, O_2 , and N_2 in feed, J/kg
\hat{h}_o	total specific enthalpy of feed to combustion chamber, J/kg
$\Delta h_{L,G,373.15}^o$	specific enthalpy of evaporation at 373.15 K, J/kg
J	nucleation rate, droplets formed/ m^3 -s
\bar{J}_j	mean nucleation rate defined by equation (108), droplets formed/ m^3 -s
$K_{p,j}$	equilibrium constant for reaction j
Kn	Knudsen number defined in terms of r
Kn_*	Knudsen number defined in terms of r_*
k	Boltzmann constant, J/molecule-K
L	latent heat of evaporation at $T_s(p_1)$, J/kg
$\tilde{\ell}$	mean free path, m
M	mass of a water droplet, kg
m	average molecular mass of gaseous mixture, kg/molecule
m_c	average molecular mass of carrier gas, kg/molecule
m_1	molecular mass of water, kg/molecule
\dot{m}	mass flow rate, kg total mixture/s
n	iteration index and atoms of carbon per molecule of fuel

Δn^i	number of droplets of kind i per mass of total mixture, droplets/kg
Pr	Prandtl number defined in terms of $c_{p,1}$ (eq. (69))
p	pressure, N/m ²
p_1	partial pressure of water vapor, N/m ²
p_∞	vapor pressure of water over a flat surface, N/m ²
p^o	standard state pressure, 0.101325 MN/m ²
Q	Kantrowitz correction factor, equation (62)
q_c	condensation coefficient
q_e	evaporation coefficient
R	universal gas constant, 8.314 J/mol-K
\bar{R}	specific gas constant for mixture, R/W , J/kg-K
R'	universal gas constant, 1.987 cal/mol-K
\bar{R}_c	specific gas constant for carrier gas, R/W_c , J/kg-K
\bar{R}_1	specific gas constant for water, R/W_1 , J/kg-K
r	droplet radius, m
r_w	nozzle wall radius, m
r_*	critical droplet radius, m
s	specific entropy of total mixture, J/kg-K
$s_{G,1}^o$	specific entropy of water vapor at standard state pressure, J/kg-K
s_L	specific entropy of liquid water, J/kg-K
$\Delta s_{L,G}^o$	specific entropy of evaporation at standard state pressure, J/kg-K
T	temperature, K
T_G	temperature of gaseous mixture, K
T_L	temperature of liquid water, K
T_R	reduced temperature, T/T_c
T_c	critical temperature of water, 647.3 K
$T_s(p_1)$	saturation temperature based on partial pressure of water vapor, K
t	time, s
Δt	time step, s
U	velocity, m/s
W	average molecular weight of gaseous mixture, kg/mol (also $W = 1/Y$)
W_c	average molecular weight of carrier gas, kg/mol
W_k	molecular weight of species k , kg/mol

w	mass of liquid water per mass of total mixture
w_c	mass of carrier gas per mass of total mixture
x	distance along nozzle measured from throat, m
Δx	computational step along nozzle, m
Y	mol number of mixture, mols/kg
Y_C, Y_H, Y_O, Y_N	equivalent total mols of elements C, H, O, and N per mass of total mixture, mols/kg
Y_k	mol number of species k , mols/kg
Y_k^o	mol number of species k in gaseous mixture at point in nozzle where $J \doteq J_{\min}$, mols/kg
$\hat{Y}_F, \hat{Y}_{O_2}, \hat{Y}_{N_2}$	mols of fuel, O_2 , and N_2 per mass of total mixture in feed, mols/kg
y_k	mol fraction of species k
Z_j	parameter defined by equation (112)
z	ratio of droplet radius to critical radius, r/r_*
α	constant in equation (78)
α_c	thermal accommodation coefficient for carrier gas interaction with water droplets
β	constant in equation (75); also, Langmuir parameter
γ	ratio of specific heats
δ	parameter defined by equation (82)
δ^*	nozzle boundary layer displacement thickness, m
ϵ	allowable iteration error
$\eta_{H,C}$	elemental ratio of hydrogen to carbon in mixture
$\eta_{N,O}$	elemental ratio of nitrogen to oxygen in mixture
θ	parameter defined by equation (75)
Λ	parameter defined by equation (76)
λ	thermal conductivity of gaseous mixture, J/s-m-K
μ	viscosity of gaseous mixture, N-s/m ²
ν	parameter defined by equation (78)
ξ	parameter defined by equation (77)
ρ	mass density, kg/m ³
σ	surface tension, N/m
ϕ	equivalence ratio
ψ	parameter defined by equation (80)
Ω	parameter defined by equation (73)
Subscripts:	
c	carrier gas

G	gaseous mixture
i	properties at interface between free molecular and continuum regimes (see appendix A)
j	location index along nozzle axis
k	chemical species index (where $k = 1$ denotes water vapor)
L	liquid water
min	minimum
n	summation index
o	stagnation conditions
s	saturation condition except in equation (12) where it is stoichiometric condition
1	water vapor
373.15	evaluated at 373.15 K
Superscripts:	
i	droplet type index
o	conditions at point in nozzle where nucleation just begins, except p^o denotes standard state pressure of 0.101325 MN/m ²
$'$	approximation
$''$	alternate approximation
$*$	sonic condition at nozzle throat

A caret (\wedge) over a symbol indicates the feed condition to combustor.

Introduction

Experimental studies of propulsion systems and aerothermal-structural systems concepts for hypersonic flight require wind tunnels that generate high enthalpy flow. One approach to achieving such flows utilizes combustion at a relatively high pressure followed by expansion of the resulting combustion products to form the test stream. A number of combustion-driven wind tunnels burning various fuels and of various sizes have been built and operated.

Fuels for these facilities include hydrogen, methane (as the major component of natural gas), and isobutane each burning with air or oxygen-enriched air. In all cases, the products of combustion contain a substantial amount of water vapor. Conditions for which condensation of water could occur depend on the equivalence ratio, temperature, and pressure in the tunnel combustion chamber, and the extent of the expansion of the combustion products in the nozzle. If liquid water does form, the process experiences entropy production and the flow properties are altered relative to an isentropic expansion. There is therefore a need to be able to predict and analyze the effects of nucleation and water droplet growth in combustion-driven wind tunnels.

A great deal of computational and experimental work has been carried out over the years on the nucleation and droplet growth of liquid water from pure steam. References 1 and 2 include reviews of previous studies and present computations and comparisons with experimental data for pure steam. One of the most recent studies has been presented by Young in references 3 and 4 and is the starting point and basis for the present work. The method presented by Young for steam is modified and extended to the rapid expansion of combustion products. This requires the addition of a scheme to compute the properties of the reacting gas mixture in the combustion chamber and the subsequent expansion along the nozzle prior to the formation of liquid water and the modification of the nucleation and droplet growth equations to account for the noncondensable components of the combustion products.

The equations are developed for a quasi-one-dimensional flow of combustion products; nucleation and droplet growth are taken into account in the development. A numerical scheme that employs these equations is presented. Sample results for selected conditions in the Langley 8-Foot High-Temperature Tunnel are also given and show the general effects of water condensation.

Development of Equations

The development of an appropriate set of equations for water condensation from a rapidly expanding flow of combustion products follows closely the approach presented by Young (refs. 3 and 4) for condensation of pure steam. In the present analysis, the tunnel stagnation conditions and the subsequent expansion along the nozzle are described by a reacting mixture of ideal gases in chemical equilibrium. The condition of chemical equilibrium is applied along the expansion until nucleation just begins, at which point the temperature is low enough so that no further reaction needs to be considered. Also the nucleation and droplet growth processes take place in a gaseous mixture of water vapor and a noncondensable carrier gas composed of the other combustion products rather than pure steam. It should be noted that no liquid water is formed while the condition of chemical equilibrium is imposed and that no chemical reaction takes place during nucleation and droplet growth. Figure 1 is a schematic of a combustion-heated wind tunnel to which this analysis is applied.

The description of the nozzle flow process from the combustion chamber through the throat and until nucleation just begins requires a set of flow equations, stoichiometric relationships, a set of equations for computing the equilibrium chemical composition, thermodynamic relations and properties for a reacting gas mixture, and a nucleation rate equation. This process is indicated as part 1 and part 2 in figure 1. Computation of the flow process for continued expansion during nucleation and droplet growth requires additional equations for transport properties, droplet growth rate, and entropy production. This process is indicated as part 3 in figure 1. The following paragraphs present the specific equations required for these processes.

Flow Equations

The continuity equation for quasi-one-dimensional nozzle flow is

$$\dot{m} = \frac{\rho_G A U}{1 - w} \quad (1)$$

where it has been assumed that liquid water and the gaseous mixture have the same velocity. Equation (1) applies along the entire expansion prior to liquid water formation with $w = 0$ as well as with liquid water present.

The momentum equation is

$$\frac{(1 - w) dp}{\rho_G} = -U dU \quad (2)$$

where again the liquid water and gaseous mixture have the same velocity.

The energy equation for adiabatic steady flow is

$$h_o = (1 - w)h_G + \sum_i w^i h_L^i + \frac{U^2}{2} \quad (3)$$

where the first term on the right-hand side of equation (3) can be written as

$$(1 - w)h_G = (1 - w - w_c)h_{G,1} + w_c h_{G,c} \quad (4)$$

Now in the region where water vapor condenses and no further chemical reaction occurs in the gas phase, the differential form of the energy equation (eq. (3)) becomes

$$\begin{aligned} (1 - w - w_c) dh_{G,1} + w_c dh_{G,c} + U dU \\ = h_{G,1} dw - \sum_i w^i dh_L^i - \sum_i h_L^i dw^i \end{aligned} \quad (5)$$

Stoichiometric Relationships

The computation of the chemical composition of a reacting gas mixture composed of the elements C, H, O, and N requires a specification of the elemental constants Y_C , Y_H , Y_O , and Y_N which represent the equivalent total number of mols of each element per mass of mixture. These four constants can be determined by specifying the elemental nitrogen-to-oxygen ratio $\eta_{N,O}$, the elemental hydrogen-to-carbon ratio $\eta_{H,C}$, the equivalence ratio ϕ , where

$$\phi = \frac{Y_H/2 + 2Y_C}{Y_O} \quad (6)$$

and the four elemental constants are related by the identity

$$12Y_C + Y_H + 16Y_O + 14Y_N = 1000 \quad (7)$$

It follows then that

$$Y_O = \frac{500}{8 + 7\eta_{N,O} + \phi[(12 + \eta_{H,C})/(4 + \eta_{H,C})]} \quad (8)$$

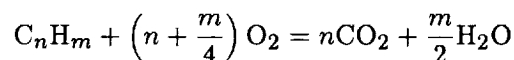
$$Y_C = \frac{2\phi Y_O}{4 + \eta_{H,C}} \quad (9)$$

$$Y_N = \eta_{N,O} Y_O \quad (10)$$

$$Y_H = \eta_{H,C} Y_C \quad (11)$$

These elemental constants will be used in the set of equations appearing in the next section.

The chemical composition of the feed stream to the combustion chamber is also required. Although it is possible to present a scheme for a more general fuel type, attention is limited to aliphatic hydrocarbons burning with a mixture of oxygen and nitrogen. For this class of fuels, the stoichiometric reaction is



and the stoichiometric ratio of fuel to oxygen in the feed is

$$\left(\frac{\hat{Y}_F}{\hat{Y}_{O_2}}\right)_s = \frac{4}{n(4 + \eta_{H,C})} \quad (12)$$

so that

$$\hat{Y}_F = \left[\frac{4\phi}{n(4 + \eta_{H,C})}\right] \hat{Y}_{O_2} \quad (13)$$

Also of course

$$\hat{Y}_{N_2} = \eta_{N,O} \hat{Y}_{O_2} \quad (14)$$

and since

$$\hat{Y}_{O_2} = \frac{Y_O}{2} \quad (15)$$

it follows that

$$\hat{Y}_{O_2} = \frac{250}{8 + 7\eta_{N,O} + \phi[(12 + \eta_{H,C})/(4 + \eta_{H,C})]} \quad (16)$$

In the flow region where nucleation and droplet growth occur, no further chemical reaction takes place so that the mixture composition changes only as a result of water condensation. The gaseous mixture composition in this region can be expressed in the following way in terms of the mass fraction of liquid water formed and the mol numbers of each species in the gaseous mixture just before any liquid water is formed. Let w represent the mass of liquid water in the stream per unit mass of total mixture (liquid water plus gaseous mixture). Also let Y_k represent the mol number of species k in the gaseous mixture and Y_k^o denote the mol number of species k in the gaseous mixture just before any liquid water is formed. Now since the number of mols of liquid water formed per unit mass of the total mixture is w/W_1 and the mass of gaseous mixture per mass of total

mixture is $(1 - w)$, it follows that the mol number of water vapor in the gaseous mixture is

$$Y_1 = \frac{Y_1^o - w/W_1}{1 - w} \quad (17)$$

in the region where nucleation and droplet growth occur. The mol numbers for the other species, that is for $k > 1$, are

$$Y_k = \frac{Y_k^o}{1 - w} \quad (18)$$

It also follows, since

$$W = \frac{1}{\sum_{k=1}^{10} Y_k} \quad (19)$$

that the average molecular weight of the gaseous mixture is

$$W = \frac{1 - w}{Y^o - w/W_1} \quad (20)$$

where

$$Y^o = \sum_{k=1}^{10} Y_k^o \quad (21)$$

Also, the mol fraction of any species in the gaseous mixture is

$$y_k = Y_k W \quad (22)$$

The average molecular weight of the carrier gas, that is for all species in the gaseous mixture except water vapor, is

$$W_c = \sum_{k=2}^{10} \frac{Y_k W_k}{Y - Y_1} \quad (23)$$

or noting that $Y = 1/W$ and using the foregoing expressions for y_k , Y_1 , Y_k , and W , it follows that

$$W_c = \sum_{k=2}^{10} \frac{y_k^o W_k}{1 - y_1^o} \quad (24)$$

which is of course independent of the amount of water condensed, w .

Equilibrium Chemical Composition

The equilibrium chemical composition of combustion products includes 10 species numbered from 1 to 10 in the following order— H_2O , CO_2 , CO , O_2 ,

H_2 , N_2 , H , O , OH , and NO . The composition is determined by the simultaneous solution of the following six chemical equilibrium relations corresponding to the six listed reactions:

For reaction I, $CO_2 + H_2 = CO + H_2O$,

$$K_{p,1} = \frac{Y_1 Y_3}{Y_2 Y_5} \quad (25)$$

For reaction II, $2CO_2 = 2CO + O_2$,

$$K_{p,2} = \frac{Y_3^2 Y_4}{Y_2^2 Y} \frac{p}{p^o} \quad (26)$$

For reaction III, $H_2 + O_2 = 2OH$,

$$K_{p,3} = \frac{Y_9^2}{Y_4 Y_5} \quad (27)$$

For reaction IV, $H_2 = 2H$,

$$K_{p,4} = \frac{Y_8^2}{Y_4 Y} \frac{p}{p^o} \quad (28)$$

For reaction V, $O_2 = 2O$,

$$K_{p,5} = \frac{Y_8^2}{Y_4 Y} \frac{p}{p^o} \quad (29)$$

For reaction VI, $O_2 + N_2 = 2NO$,

$$K_{p,6} = \frac{Y_{10}^2}{Y_4 Y_6} \quad (30)$$

and the four elemental balance equations:

$$Y_H = 2Y_1 + 2Y_5 + Y_7 + Y_9 \quad (31)$$

$$Y_O = Y_1 + 2Y_2 + Y_3 + 2Y_4 + Y_8 + Y_9 + Y_{10} \quad (32)$$

$$Y_N = 2Y_6 + Y_{10} \quad (33)$$

$$Y_C = Y_2 + Y_3 \quad (34)$$

The expression for $K_{p,j}$ is

$$K_{p,j} = \exp \left(\sum_{n=1}^6 B_{n,j} T_G^{n-2} \right) \quad (35)$$

where the constant coefficients $B_{n,j}$ are given in appendix B. The constants Y_C , Y_H , Y_O , and Y_N in the four elemental balance equations are determined

from equations (8) through (11) and the specification of $\eta_{N,O}$, $\eta_{H,C}$, and ϕ .

Thermodynamic Relations and Properties

The starting point for determining the thermodynamic properties of a mixture is an equation for the molar heat capacity at constant pressure of each chemical species expressed as

$$C_{p,k} = \sum_{n=1}^6 A_{n,k} T_G^{n-2} \quad (36)$$

where $A_{n,k}$ is a set of constant coefficients given in appendix B for each species over a temperature range. In some cases, the specific heat capacity at constant pressure is useful and can be written as

$$c_{p,k} = \frac{C_{p,k}}{W_k} \quad (37)$$

In addition to this expression for the k th species, expressions for the specific heat capacity at constant pressure and the ratio of specific heats for water vapor are needed; that is,

$$c_{p,1} = \frac{\sum_{n=1}^6 A_{n,1} T_G^{n-2}}{W_1} \quad (38)$$

and

$$\gamma_1 = \frac{c_{p,1}}{c_{p,1} - \bar{R}} \quad (39)$$

Similar expressions for the carrier gas are also needed for computations of droplet growth and can be written as

$$c_{p,c} = \frac{\sum_{k=2}^{10} y_k^o C_{p,k}}{(1 - y_1^o) W_c} \quad (40)$$

and

$$\gamma_c = \frac{c_{p,c}}{c_{p,c} - \bar{R}_c} \quad (41)$$

The specific enthalpy of the gaseous mixture can be obtained from the equation for $C_{p,k}$, integration, and summation over all species to give

$$h_G = \sum_{k=1}^{10} Y_k \left[A_{1,k} \ln T_G + \sum_{n=2}^6 \frac{A_{n,k} T_G^{n-1}}{n-1} + A_{7,k} \right] \quad (42)$$

where the additional constant coefficients $A_{7,k}$ include the standard state enthalpy of formation of each species at the reference temperature of 298.15 K.

Numerical values of $A_{7,k}$ are given in appendix B. The units for h_G are joules per kilogram of gaseous mixture. An expression for the specific enthalpy of water vapor in the mixture is also needed; that is,

$$h_{G,1} = \frac{\left[A_{1,1} \ln T_G + \sum_{n=2}^6 \frac{A_{n,1} T_G^{n-1}}{n-1} + A_{7,1} \right]}{W_1} \quad (43)$$

The units of $h_{G,1}$ are joules per kilogram of water vapor.

The specific entropy of the gaseous mixture can also be obtained from the expression for $C_{p,k}$, integration, and summation over all species to give

$$s_G = \sum_{k=1}^{10} Y_k \left[\frac{-A_{1,k}}{T_G} + (A_{2,k} - R') \ln T_G + \sum_{n=3}^6 \frac{A_{n,k} T_G^{n-2}}{n-2} + A_{8,k} \right] - \bar{R} \ln \rho_G - \bar{R} \ln \left(\frac{R}{p^o} \right) - R \sum_{k=1}^{10} Y_k \ln Y_k \quad (44)$$

where $A_{8,k}$ includes the standard state entropy of formation of species k at the reference temperature of 298.15 K. Numerical values are given in appendix B. For some applications it is convenient to invert this equation to express ρ_G as a function of s_G , T_G , and the set of mol numbers Y_k ; that is,

$$\rho_G = \exp \left[\frac{G - s_G - \bar{R} \ln (R/p^o) - R \sum_{k=1}^{10} Y_k \ln Y_k}{\bar{R}} \right] \quad (45)$$

where

$$G = \sum_{k=1}^{10} Y_k \left[\frac{-A_{1,k}}{T_G} + (A_{2,k} - R') \ln T_G + \sum_{n=3}^6 \frac{A_{n,k} T_G^{n-2}}{n-2} + A_{8,k} \right] \quad (46)$$

The equation of state for the gaseous mixture is

$$p = \rho_G \bar{R} T_G \quad (47)$$

where $\bar{R} = \frac{R}{W}$ and $W = \left(\sum_{k=1}^{10} Y_k \right)^{-1}$

Computations in the flow region where nucleation and droplet growth can occur require additional equations for the enthalpy and entropy of liquid water. An equation for the specific enthalpy of liquid water is obtained by starting with the specific enthalpy of evaporation of water at 1 atm and 373.15 K from reference 5; that is, $\Delta h_{L,G,373.15}^o = 2.2570 \times 10^6$ J/kg. Then using equation (43) at $T = 373.15$ K and the coefficients $A_{n,1}$ given in table B1(a), it follows that $h_{G,1,373.15} = -13.2933 \times 10^6$ J/kg. Also, the heat capacity of liquid water in the region of interest is essentially constant and is $c_L = 4.2 \times 10^3$ J/kg-K. Now since

$$h_L - h_{L,373.15} = (4.2 \times 10^3)(T - 373.15) \quad (48)$$

and

$$\Delta h_{L,G,373.15}^o = h_{G,1,373.15} - h_{L,373.15} \quad (49)$$

it follows that the specific enthalpy of liquid water is

$$h_L = (4.2 \times 10^3)T - (17.1175 \times 10^6) \quad (50)$$

where the units of h_L are joules per kilogram of liquid water.

The specific entropy of liquid water can be obtained in a similar way. The specific entropy of evaporation of water at 1 atm and 373.15 K is

$$\Delta s_{L,G,373.15}^o = \frac{\Delta h_{L,G,373.15}^o}{373.15} = 6.0485 \times 10^3 \text{ J/kg-K}$$

The entropy of water vapor at 1 atm and 373.15 K is obtained by using the equation

$$s_{G,1}^o = \frac{\left[-A_{1,1}/T_G + A_{2,1} \ln T_G + \sum_{n=3}^6 \frac{A_{n,1} T_G^{n-2}}{n-2} + A_{8,1} \right]}{W_1} \quad (51)$$

and the coefficients $A_{n,1}$ given in table B1(a) so that $s_{G,1,373.15}^o = 10.905 \times 10^3$ J/kg-K. Now since

$$s_L - s_{L,373.15} = (4.2 \times 10^3) \ln \frac{T}{373.15} \quad (52)$$

and

$$\Delta s_{L,G,373.15}^o = s_{G,1,373.15}^o - s_{L,373.15} \quad (53)$$

it follows that the specific entropy of liquid water is

$$s_L = 4.2 \times 10^3 \ln T - 20.0149 \times 10^3 \quad (54)$$

where the units of s_L are joules per kilogram of liquid water-kelvin.

An equation for the specific latent heat of evaporation of water at a temperature T is also needed and is

$$L = h_{G,1} - h_L \quad (55)$$

It then follows from equation (50) that

$$L = h_{G,1} - 4.2 \times 10^3 T + 17.1175 \times 10^6 \quad (56)$$

where $h_{G,1}$ is evaluated at T and the units of L are joules per kilogram of water.

The vapor pressure of water is also required. An expression for the vapor pressure of water over a flat surface as a function of temperature was obtained by fitting a curve to the tabulated values given in reference 5; that is,

$$p_\infty = \exp \left(55.897 - \frac{6641.7}{T} - 4.4864 \ln T \right) \quad (57)$$

where p_∞ has units of newtons per meter².

The surface tension of water is represented by the equation given by Young (ref. 4); that is,

$$\sigma = (82.27 + 75.612T_R - 256.889T_R^2 + 95.928T_R^3) \times 10^{-3} \quad (58)$$

where $T_R = \frac{T}{T_c}$ with T_c denoting the critical temperature of water. The units of σ are newtons per meter.

Finally, the critical droplet radius is obtained from the well-known equation

$$r_* = \frac{2\sigma}{\rho_L \bar{R}_1 T_G \ln(p_1/p_\infty)} \quad (59)$$

where $p_1 = y_1 p$ and r_* has units of meters. Droplets larger than r_* tend to grow while droplets less than r_* tend to evaporate.

Nucleation Rate

The nucleation rate equation given by Young can be modified to take into account a carrier gas by replacing the gas density in Young's equation which is for pure steam by the density of water vapor. This follows from the argument that nucleation depends on collisions between water molecules in the gaseous phase and clusters of water molecules, both of which are proportional to the density of water vapor. Now since the density of water vapor in a gaseous mixture can be expressed as

$$\rho_{G,1} = \frac{y_1 m_1}{m} \rho_G \quad (60)$$

the nucleation rate equation for a gaseous mixture that includes a carrier gas becomes

$$J = \frac{q_c}{1+Q} \left(\frac{y_1 m_1}{m} \right)^2 \left(\frac{2\sigma}{\pi m_1^3} \right)^{1/2} \frac{\rho_G^2}{\rho_L} \times \exp \left(\frac{-4\pi r_*^2 \sigma}{3kT_G} \right) \quad (61)$$

where q_c is the condensation coefficient which Young argued to be unity and

$$Q = \frac{2(\gamma_1 - 1)}{\gamma_1 + 1} \frac{L}{R_1 T_G} \left(\frac{L}{R_1 T_G} - \frac{1}{2} \right) \quad (62)$$

is the nonisothermal correction factor given by Kantrowitz in reference 6.

Transport Properties

The need to consider transport processes is limited to the flow region in which droplet growth can occur. The temperature in this region is relatively low so that viscosity and thermal conductivity data are required over a rather narrow temperature range. Furthermore, only seven chemical species (H_2O , CO_2 , CO , O_2 , H_2 , N_2 , and NO) are present in significant quantities at these temperatures.

The viscosity of the gaseous mixture can be obtained by starting with an expression for the viscosity of each species in the pure state and then applying a mixing rule. The viscosity of each pure species can be represented by a polynomial

$$\mu_k = \sum_{n=1}^4 D_{n,k} T_G^{n-1} \quad (63)$$

where the constant coefficients for each species $D_{n,k}$ are given in appendix B. The viscosity of the gaseous mixture containing these species can then be obtained from the expression (ref. 7)

$$\mu = \sum_{k=1}^{10} \frac{\mu_k}{1 + \frac{1}{Y_k} \sum_{\substack{\ell=1 \\ \ell \neq k}}^{10} Y_\ell \phi_{k,\ell}} \quad (64)$$

where

$$\phi_{k,\ell} = \frac{[1 + (\mu_k/\mu_\ell)^{1/2} (W_\ell/W_k)^{1/4}]^2}{\{8[1 + (W_k/W_\ell)]\}^{1/2}} \quad (65)$$

The thermal conductivity of the gaseous mixture can also be obtained by starting with a polynomial expression in terms of temperature for each pure species

$$\lambda_k = \sum_{n=1}^4 E_{n,k} T_G^{n-1} \quad (66)$$

where the constant coefficients for each species $E_{n,k}$ are given in appendix B. The thermal conductivity of the gaseous mixture can then be obtained by using the expression (ref. 8)

$$\lambda = \frac{1}{2} \left[W \sum_{k=1}^{10} Y_k \lambda_k + \frac{1}{W \sum_{k=1}^{10} Y_k / \lambda_k} \right] \quad (67)$$

Finally, the equations for the mean free path, Prandtl number, and Knudsen number are

$$\dagger \tilde{\ell} = 1.5\mu \frac{\sqrt{RT_G}}{p} \quad (68)$$

$$Pr = \frac{c_{p,1}\mu}{\lambda} \quad (69)$$

$$Kn = \frac{\tilde{\ell}}{2r} \quad (70)$$

and

$$Kn_* = \frac{\tilde{\ell}}{2r_*} \quad (71)$$

where the specific heat at constant pressure for water vapor is used to define the Prandtl number.

Droplet Growth Rate

The integrated droplet growth equation given by Young for droplets with $z = \frac{r}{r_*} \geq 1.1$ can be written as

$$\begin{aligned} \frac{\theta^3}{\theta+1} \ln \frac{z_{j+1} + \theta}{z_j + \theta} + \left(\frac{1}{\theta+1} + \Omega \right) \ln \frac{z_{j+1} - 1}{z_j - 1} \\ + (\Omega + 1 - \theta)(z_{j+1} - z_j) \\ + \frac{1}{2} (z_{j+1}^2 - z_j^2) = \Lambda \Delta t \end{aligned} \quad (72)$$

[†] The constant of 1.5 used by Young is somewhat smaller than $3\sqrt{\pi/8} = 1.88$ from simplified kinetic theory and somewhat larger than $\frac{\sqrt{\pi/8}}{0.499} = 1.26$ from a considerably more elaborate calculation.

This equation also applies in the case with a carrier gas present when Ω is defined as

$$\Omega = \frac{\xi(1-\nu)Kn_*}{Pr f} \quad (73)$$

where

$$f = y_1 \left(\frac{m_1}{m} \right)^{1/2} + (1 - y_1) \left(\frac{m_c}{m} \right)^{1/2} \left[\frac{(\gamma_c + 1)\gamma_1 c_{p,c}}{(\gamma_1 + 1)\gamma_c c_{p,1}} \right] \alpha_c \quad (74)$$

The derivation of the factor f is given in appendix A.

Expressions for the other parameters θ , Λ , ξ , and ν are

$$\theta = 2\beta Kn_* \quad (75)$$

$$\Lambda = \lambda \frac{[T_s(p_1) - T_G]}{L \rho_L r_*^2} \quad (76)$$

$$\xi = \frac{\sqrt{8\pi}}{1.5} \frac{2\gamma_1}{\gamma_1 + 1} \quad (77)$$

and

$$\nu = \frac{\bar{R}_1 T_s(p_1)}{L} \left[\alpha + \frac{1}{2} - \frac{2 - q_c}{2q_c} \frac{\gamma_1 + 1}{2\gamma_1} \frac{c_{p,1} T_s(p_1)}{L} \times \frac{f}{y_1} \left(\frac{m}{m_1} \right)^{1/2} \right] \quad (78)$$

The saturation temperature $T_s(p_1)$ is based on the partial pressure of water vapor in the mixture, and γ_1 and $c_{p,1}$ are for water vapor. Also note that the expression for ν contains a term $+1/2$ rather than $-1/2$ given by Young. This difference is believed to be due to a typographical error in Young's paper.

The integrated droplet growth equation given by Young for droplets with $z = \frac{r}{r_*} < 1.1$ is

$$z_{j+1} = 1 + \frac{\tau_{*,j}}{\tau_{*,j+1}} (z_j - 1) \exp(\psi \Delta t) - \frac{1}{\psi \tau_{*,j+1}} \frac{dr_*}{dt} \exp(\psi \Delta t - 1) \quad (79)$$

where the subscripts j and $j+1$ denote adjacent locations in the flow direction and Δt is the corresponding time interval. This equation applies to the case

with a carrier gas present when ψ is defined as

$$\psi = \frac{fp}{r_j \sqrt{2\pi \bar{R} T_G}} \frac{\gamma_1 + 1}{2\gamma_1} \frac{c_{p,1}}{L \rho_L} \frac{1}{1 - \nu} [T_s(p_1) - T_G] \quad (80)$$

where f and ν are given by equations (74) and (78).

The temperature of the liquid droplets is also required. Young has developed the following equation for T_L which depends on T_G , $T_s(p_1)$, r_* , and r :

$$T_L = T_G + \frac{(1 - r_*/r)[T_s(p_1) - T_G]}{1 - \nu \delta} \quad (81)$$

where

$$\delta = \frac{\xi Kn / Pr}{1 + \frac{f}{2\beta Kn} + \frac{\xi Kn}{Pr}} \quad (82)$$

and ξ is given by equation (77). It should be noted that equations (72) and (79) imply that the droplets retain their identity as they grow and do not agglomerate.

Entropy Production Equation

The approach taken by Young was to replace the differential form of the momentum equation with an expression for the increase in entropy due to water condensation. The differential change in entropy given by Young due to liquid water formation also applies to a mixture containing a carrier gas if expressed as

$$ds = \{L - c_{p,1}[T_s(p_1) - T_G]\} \left[\frac{1}{T_G} - \frac{1}{T_s(p_1)} \right] dw \quad (83)$$

where the saturation temperature $T_s(p_1)$ is based on the partial pressure of water vapor in the mixture p_1 , the specific heat of water vapor $c_{p,1}$ is used, and the latent heat L is evaluated at $T_s(p_1)$.

Numerical Solution

The foregoing set of equations can now be used to obtain a numerical solution for the adiabatic expansion of combustion products with nucleation and water droplet growth. The numerical solution is divided into three successive parts as indicated in figure 1.

Part 1 of Numerical Solution—Stagnation Conditions and Mass Flow Rate

Part 1 of the numerical solution involves the specification of the feed conditions to the combustor, the determination of the adiabatic flame temperature,

the computation of the chemical composition of combustion products in the combustor at a stagnation temperature that allows for heat loss, and the determination of the mass flow rate.

Feed conditions. The first step in computing the stagnation conditions in the combustion chamber is to define the hydrogen-to-carbon ratio $\eta_{H,C}$ and the number of atoms of carbon in a molecule of fuel n ; the nitrogen-to-oxygen ratio $\eta_{N,O}$; the fuel equivalence ratio ϕ ; the feed temperatures of the fuel, air, and oxygen to the combustion chamber, \hat{T}_F , \hat{T}_{air} , and \hat{T}_{O_2} ; and the pressure in the combustion chamber, p_o . The selection of the fuel and the feed temperatures determines the specific enthalpy of the fuel \hat{h}_F as well as \hat{h}_{O_2} and \hat{h}_{N_2} .

The feed composition in terms of \hat{Y}_F , \hat{Y}_{O_2} , and \hat{Y}_{N_2} may be found by first solving equation (16) for \hat{Y}_{O_2} and then equations (13) and (14) for \hat{Y}_F and \hat{Y}_{N_2} . The specific total enthalpy of the feed can then be computed from the equation

$$\hat{h}_o = \hat{Y}_F \hat{h}_F + \hat{Y}_{O_2} \hat{h}_{O_2} + \hat{Y}_{N_2} \hat{h}_{N_2} \quad (84)$$

Adiabatic flame temperature. The adiabatic flame temperature and the corresponding chemical equilibrium composition are determined by the simultaneous solution of the elemental balance expressions (eqs. (31) through (34)), the equilibrium relations (eqs. (25) through (30)), and the specific enthalpy of the mixture with $h_G = \hat{h}_o$ (eq. (42)). Auxiliary equations for the equilibrium constants (eq. (35)) and the elemental constants (eqs. (8) through (11)) are also required. A solution is obtained by iteration for flame temperature T_f .

Equations (25) through (34) are solved simultaneously by the method of successive approximations. For flame temperatures up to 2000 K and fuel lean conditions, the major chemical species are H_2O , CO_2 , CO , O_2 , and N_2 . Although significant amounts of the other five species may be present, estimates for the five major species noted can be used for a reasonable initial approximation. If an initial estimate of the ratio of the number of mols of CO_2 to total mols of carbon in the mixture $a_{2,C}$ is made, and equations (31) through (34) are used with $Y_5 = Y_7 = Y_8 = Y_9 = Y_{10} = 0$, it follows that a first approximation for the mol numbers of the five major species and the total mol number of the mixture is

$$Y_1 = \frac{Y_H}{2} \quad (85)$$

$$Y_2 = a_{2,C} Y_C \quad (86)$$

$$Y_3 = Y_C - Y_2 \quad (87)$$

$$Y_4 = \frac{Y_O - Y_C - Y_1 - Y_2}{2} \quad (88)$$

$$Y_6 = \frac{Y_N}{2} \quad (89)$$

$$Y = \frac{Y_H + Y_O + Y_N + Y_C - Y_1 - Y_2}{2} \quad (90)$$

If equations (25) through (30) are now also used along with equations (31) through (34), the following set of equations can be used to determine the chemical composition for all 10 species through a series of successive approximations:

$$Y_3 = Y_2 \left(\frac{K_{p,2} Y}{Y_4} \frac{p^o}{p} \right)^{1/2} \quad (91)$$

$$Y_5 = \frac{Y_1 Y_3}{K_{p,1} Y_2} \quad (92)$$

$$Y_{10} = (K_{p,6} Y_4 Y_6)^{1/2} \quad (93)$$

$$Y_6 = \frac{Y_N - Y_{10}}{2} \quad (94)$$

$$Y_9 = (K_{p,3} Y_4 Y_5)^{1/2} \quad (95)$$

$$Y_7 = \left(K_{p,4} Y_5 Y \frac{p^o}{p} \right)^{1/2} \quad (96)$$

$$Y_8 = \left(K_{p,5} Y_4 Y \frac{p^o}{p} \right)^{1/2} \quad (97)$$

$$Y_1 = \frac{Y_H - 2Y_5 - Y_7 - Y_9}{2} \quad (98)$$

$$Y_2 = Y_C - Y_3 \quad (99)$$

$$Y_4 = \frac{Y_O - Y_C - Y_1 - Y_2 - Y_8 - Y_9 - Y_{10}}{2} \quad (100)$$

$$Y_4 = \frac{\left[Y_4 + \frac{Y_O - Y_C - Y_1 - Y_2 - Y_8 - Y_9 - Y_{10}}{2} \right]}{2} \quad (101)$$

$$Y = \sum_{k=1}^{10} Y_k \quad (102)$$

It should be noted that equation (100) led to step-to-step oscillations in the solution for higher temperatures. In order to avoid this problem, equation (100) was rewritten as equation (101) to provide some damping. The numerical value of Y_4 computed in the previous iteration step is used in the

right-hand side of equation (101). After a stable solution for the mol numbers Y_k for $k = 1$ to 10 is achieved for a given temperature, the corresponding specific enthalpy of the mixture h_G is computed from equation (42) and compared with the known total feed enthalpy \hat{h}_o . If h_G turns out to be less than \hat{h}_o , the next approximation to the temperature is increased and if greater, decreased. The final solution for the adiabatic flame temperature is obtained when $h_G = \hat{h}_o$.

Stagnation conditions. This study does not attempt to compute the heat loss from the combustor, however, the influence of an arbitrary heat loss has been taken into account by assuming a stagnation temperature T_o that is somewhat less than the adiabatic flame temperature. The chemical composition at T_o can then be determined directly by using the scheme just presented. The stagnation enthalpy h_o and the stagnation entropy s_o are then computed from equations (42) and (44).

Mass flow rate. The mass flow rate is determined in the following way. An isentropic expansion from the combustion chamber is assumed and the mass flux $\rho_G U$ computed along the nozzle to find the maximum value of $\rho_G U$. Since h_o and s are constant along the expansion, all flow properties can be computed at a selected temperature that is less than T_o . This computation uses an iteration on the pressure.

The choice of an approximate pressure, say p' , at the selected temperature T allows the computation of a chemical equilibrium composition. This in turn permits the direct computation of the density by equations (45) and (46). The resulting density ρ_G and composition can then be used in equation (47) to compute a pressure p . A comparison between p' and p indicates the need to continue the iteration process. When the iteration scheme gives a value of p sufficiently close to p' , the pressure is determined. The flow velocity U at this state is then computed from equation (3) with no liquid water present; that is,

$$U = [2(h_o - h_G)]^{1/2} \quad (103)$$

The mass flux $\rho_G U$ can therefore be found at selected temperatures corresponding to successive locations along the nozzle. The maximum mass flux $\rho_G^* U^*$ occurs at the nozzle throat where the nozzle cross-sectional area is A^* . The mass flow rate is given then by equation (1) with no liquid water present; that is,

$$\dot{m} = \rho_G^* U^* A^* \quad (104)$$

This is the mass flow rate of the total mixture along the entire length of the nozzle including the downstream conditions with liquid water formation.

Part 2 of Numerical Solution—Isentropic Expansion and Beginning of Nucleation

Part 2 of the numerical solution involves the computation from the nozzle throat to the beginning of nucleation. It is assumed that the flow expands isentropically and remains in chemical equilibrium with no liquid water formation. At each step along the nozzle the nucleation rate is computed to determine at what point to include nucleation and liquid droplet growth.

Isentropic expansion. The isentropic expansion from the nozzle throat is obtained by noting that $s = s_o$ and $h_o = \text{Constant}$ along the nozzle. Starting at T^* and p^* , a temperature T less than T^* is selected. The pressure is then determined by iteration and the values of ρ_G , h_G , and U computed by the scheme given in part 1 of the numerical solution. The area of the nozzle can then be computed from equation (1) with $w = 0$; that is,

$$A = \frac{\dot{m}}{\rho_G U} \quad (105)$$

The location of this particular point along the nozzle is then determined by using the relationship that defines the cross-sectional area as a function of nozzle position x . This computation in general requires the inversion of the expression of A as a function of x or an iteration to find x for a given value of A .

Beginning of nucleation. The nucleation rate J is computed from equation (61) where the appropriate values of γ_1 , $h_{G,1}$, L , p_∞ , σ , and τ_* are obtained from equations (39), (43), (56), (57), (58), and (59), respectively. This computed value of J is compared with a value J_{\min} chosen such that a smaller value of J does not generate enough nuclei to affect the flow throughout the nozzle. Successively lower values of T are taken along the nozzle until $J \geq J_{\min}$. At this point and downstream, the number of nuclei formed is taken into account, and the droplet growth equations are used.

Part 3 of Numerical Solution—Nucleation and Droplet Growth

Part 3 of the numerical solution deals with the computation of the nucleation process to determine the number of droplets formed at successive locations along the nozzle and the subsequent growth of the liquid water droplets. The starting point is

the condition determined in part 2 of the numerical solution where the nucleation rate just exceeds a threshold value. The index j is used to denote a location along the nozzle, starting with $j = 1$ at the beginning of part 3 (fig. 1), where all properties are known. This also includes the chemical composition of the gas phase. Since essentially no further chemical reaction takes place once nucleation and droplet growth occur, the only change in the gaseous mixture composition is due to the formation of liquid water. The appropriate expressions for Y_1, Y_k (with $k = 2, 3, \dots, 6$), and W at any position along the nozzle are thus given by equations (17), (18), and (19). The computation proceeds in general at location j where $T, p, \rho, y_1, U, s, A, x$, and w are known. All other required parameters at j can be computed from this set. Note also that all properties at $j - 1$ are known.

Computational steps along nozzle and nozzle area.

The first step in the determination of properties at $j + 1$ is to increase x_j by Δx so that

$$x_{j+1} = x_j + \Delta x \quad (106)$$

and to determine the nozzle area from the expression

$$A_{j+1} = f(x_{j+1}) \quad (107)$$

An iteration scheme based on adjusting T_{j+1} as the primary variable is then used to find a solution for all properties at $j + 1$. Secondary iterations within the loop for T_{j+1} are also required.

Gas temperature. The first approximation for the gas temperature at $j + 1$ is $T_{j+1} = T_j$ and it is further assumed that initially $p_{j+1} = p_j$ and $U_{j+1} = U_j$. The value of T_{j+1} is adjusted as a result of each iteration step, and $T'_{j+1} = T_{j+1}$ is defined at this point and used to test for convergence.

Formation of new droplets. The nucleation rate is assumed to vary as $\exp(kx)$ as suggested by Young, so that the appropriate mean nucleation rate expressed in terms of new droplets formed per unit volume per unit time at j over the volume from $j - \frac{1}{2}$ to $j + \frac{1}{2}$ is the logarithmic mean value; that is,

$$\bar{J}_j = \frac{J_{j+1/2} - J_{j-1/2}}{\ln \frac{J_{j+1/2}}{J_{j-1/2}}} \quad (108)$$

where $J_{j+1/2}$ and $J_{j-1/2}$ are computed from equation (61). The number of new droplets formed at j per unit mass of total mixture is therefore

$$\Delta n^i = \frac{\bar{J}_j A_j \Delta x}{\dot{m}} \quad (109)$$

Although the droplet size of this set formed at j will change as it moves downstream, the number Δn^i in the set will remain constant unless some of the droplets evaporate. Agglomeration of droplets is not taken into account in these calculations. Note that a set of droplets characterized by a single index i will be formed at successive positions along the nozzle. At any position j , there could be as many as j sets of droplets each with a radius of r_j^i in the amount of Δn^i droplets per mass of total mixture.

Droplet growth. The computation of the droplet radius at $j + 1$ employs equation (72) and appropriate auxiliary equations for $z_j^i = \frac{r_j^i}{r_{*,j}} \geq 1.1$ or equation (79) and auxiliary equations for $z_j^i = \frac{r_j^i}{r_{*,j}} < 1.1$. Either equation requires the time interval that corresponds to the step size Δx ; that is,

$$\Delta t = \frac{2\Delta x}{U_j + U_{j+1}} \quad (110)$$

It should be noted that the derivation of equation (72) by Young used the argument that the properties of the gaseous mixture do not change between locations j and $j + 1$. This means that equation (72) can be used to compute r_{j+1}^i with only knowledge of properties at j . The solution for droplets in the size range of $z_j^i \geq 1.1$ can be obtained by rewriting equation (72) as

$$F = Z_{j+1} - Z_j - \Lambda \Delta t \quad (111)$$

where

$$\begin{aligned} Z_j = & \frac{\theta^3}{\theta + 1} \ln(z_j^i + \theta) \\ & + \left(\frac{1}{\theta + 1} + \Omega \right) \ln(z_j^i - 1) \\ & + (\Omega + 1 - \theta) z_j^i + \frac{1}{2} z_j^{i2} \end{aligned} \quad (112)$$

The application of a Newton iteration scheme requires dF/dz_{j+1}^i which is

$$\begin{aligned} \frac{dF}{dz_{j+1}^i} = & \frac{\theta^3}{(\theta + 1)(z_{j+1}^i + \theta)} \\ & + \frac{1 + \Omega(\theta + 1)}{(\theta + 1)(z_{j+1}^i - 1)} + z_{j+1}^i \\ & + (\Omega + 1 - \theta) \end{aligned} \quad (113)$$

so that the n th iteration gives

$$z_{j+1}^i(n+1) = z_{j+1}^i(n) - \frac{F(n)}{dF(n)/dz_{j+1}^i} \quad (114)$$

The droplet radius at $j+1$ when the iteration has been completed is

$$r_{j+1}^i = z_{j+1}^i r_{*,j} \quad (115)$$

Equation (79) is used for the smaller droplets when $z_j^i < 1.1$. In this case, the solution for z_{j+1}^i requires knowledge of $r_{*,j+1}$ as well as properties at j . An expression for dr_*/dt is

$$\frac{dr_*}{dt} = \frac{r_{*,j+1} - r_{*,j}}{\Delta t} \quad (116)$$

It should be noted that Young's analysis assumed that ψ in equation (79) and given by equation (80) is a constant over the interval from j to $j+1$ but that the solution for z_{j+1}^i from equation (79) requires knowledge of $r_{*,j+1}$. This means that the computation of r_{j+1}^i when $z_j^i < 1.1$ must use successively revised values of $r_{*,j+1}$ that correspond to the successively revised values of T_{j+1} .

Mass of liquid water. The mass of liquid water droplets that have a radius r_{j+1}^i is $\frac{4}{3}\pi\rho_L (r_{j+1}^i)^3$ so that the mass of liquid water per total mass of mixture for all droplets of type i at $j+1$ is

$$w_{j+1}^i = \frac{4}{3}\pi\rho_L (r_{j+1}^i)^3 \Delta n^i \quad (117)$$

The total mass of liquid water per total mass of mixture at $j+1$ is

$$w_{j+1} = \sum_{i=1}^{j+1} w_{j+1}^i \quad (118)$$

Enthalpy and entropy of liquid water. Now in order to compute the enthalpy and entropy of the liquid water in the mixture, the temperature of the liquid droplets of each type i , $T_{L,j+1}^i$, must be determined from equation (81). The enthalpy of the liquid at $j+1$ can then be computed from equation (50) using $T_{L,j+1}^i$ to get $h_{L,j+1}^i$ and $h_{L,j+1}$ is obtained from

$$h_{L,j+1} = \sum_i w_{j+1}^i h_{L,j+1}^i \quad (119)$$

The entropy of the liquid water is computed likewise from equation (54) using $T_{L,j+1}^i$ to get $s_{L,j+1}^i$ so that

$$s_{L,j+1} = \sum_i w_{j+1}^i s_{L,j+1}^i \quad (120)$$

Entropy production. The next step is to compute the entropy increase due to liquid water formation by equation (83) with ds replaced by Δs_j and dw by Δw_j where

$$\Delta w_j = w_{j+1} - w_j \quad (121)$$

The temperature and pressure used to determine properties in equation (83) are

$$T_G = \frac{T_{G,j+1} + T_{G,j}}{2} \quad (122)$$

and

$$p = \frac{p_{j+1} + p_j}{2} \quad (123)$$

The value of L is evaluated at $T_s(p_1)$, and $c_{p,1}$ is a very weak function of temperature so it can be evaluated at T_G . The entropy of the total mixture can therefore be written as

$$s_{j+1} = s_j + \Delta s_j \quad (124)$$

Two-level iteration to determine T_G . At this point, the iteration scheme proceeds with an attempt to find a value of $T_{G,j+1}$ that satisfies the independent computation of $s_{G,j+1}$. Simultaneously an iteration is carried out to determine a value of $\rho_{G,j+1}$ by using the known area at $j+1$, A_{j+1} , and the mass flow equation. The two iteration schemes are as follows:

1. Iteration using entropy of gas mixture: One equation for the entropy of the gaseous mixture can be written as

$$s_{G,j+1}'' = \frac{s_{j+1} - s_{L,j+1}}{1 - w_{j+1}} \quad (125)$$

where all terms on the right-hand side have been computed. A second and independent equation is given by equation (44) from which $s_{G,j+1}'$ is computed using $\rho_{G,j+1}$ and $T_{G,j+1}$. The iteration at this point assumes that $s_{G,j+1}''$ is correct, fixes $\rho_{G,j+1}$, and adjusts $T_{G,j+1}$ until

$$\frac{(s_G'' - s_G')_{j+1}}{c_p - \bar{R}} < \epsilon \quad (126)$$

where

$$c_p = \sum_k Y_k C_{p,k}$$

If this condition is not satisfied, the value of $T_{G,j+1}$ is revised according to the expression

$$T_{j+1}(n+1) = T_{j+1}(n) \exp \left[\frac{(s''_G - s'_G)_{j+1}}{c_p - \bar{R}} \right] \quad (127)$$

where $T_{j+1} = T_{G,j+1}$.

2. Iteration using nozzle area: After the condition in equation (126) is satisfied, T_{j+1} is used in equation (42) to compute $h'_{G,j+1}$. The specific enthalpy of the total mixture is then computed from

$$h'_{j+1} = (1 - w_{j+1})h'_{G,j+1} + h_{L,j+1} \quad (128)$$

The value of U at $j+1$ is then computed from

$$U_{j+1} = [2(h_o - h'_{j+1})]^{1/2} \quad (129)$$

A value for the cross-sectional area of the nozzle at $j+1$ is then computed from equation (1); that is,

$$A'_{j+1} = \frac{\dot{m}(1 - w_{j+1})}{\rho_{G,j+1}U_{j+1}} \quad (130)$$

and compared with the known area A_{j+1} by using the expression

$$\frac{|A'_{j+1} - A_{j+1}|}{A_{j+1}} < \varepsilon \quad (131)$$

If this condition is not satisfied, the density of the gaseous mixture is computed from the equation

$$\rho_{G,j+1} = \frac{\dot{m}(1 - w_{j+1})}{A_{j+1}U_{j+1}} \quad (132)$$

and the iteration process returns to the computation of $s'_{G,j+1}$ using this value of $\rho_{G,j+1}$ and the last computed value of $T_{G,j+1}$. The iteration continues until the condition in equation (131) is satisfied after which p_{j+1} is computed from equation (47).

The iteration for T_{j+1} now includes the test that

$$\frac{|T_{j+1} - T'_{j+1}|}{T'_{j+1}} < \varepsilon \quad (133)$$

If this test is not satisfied, the iteration process returns to the beginning (gas temperature) with T_{j+1} equal to its last value. When this test is satisfied j is increased by 1 with x increased by Δx (step along the nozzle and nozzle area). This process is continued to the nozzle exit.

Computer Program

A computer program, FIRACON, has been developed to solve the finite-rate condensation problem using the solution technique described in the present paper. The program is written in FORTRAN Version 5 language for the CDC® CYBER series digital computer system, model 860, with Network Operating System. The program requires approximately 134000 octal locations of core storage, and a typical case requires approximately 200 seconds of central processing unit time. Program input requirements and operating instructions are summarized in the code which is included as appendix C.

Application of Computation Scheme to Langley 8-Foot High-Temperature Tunnel

The numerical scheme presented in the previous section has been applied to the Langley 8-Foot High-Temperature Tunnel (8'HTT) for a selected set of operating conditions. The 8'HTT is a large combustion-driven wind tunnel that burns natural gas (mostly methane) and air at high pressure in a cylindrical combustor approximately 1 m in diameter and 7 m long. The combustion products which are primarily H_2O , CO_2 , O_2 , and N_2 with smaller amounts of H_2 , CO , H , O , NO , and OH , expand as the test gas from the combustor through an axisymmetric conical-contoured nozzle to a test section with a diameter of approximately 2.4 m (8 ft). The nozzle length is approximately 16 m.

Numerical results are presented for five cases that correspond to operating conditions of the 8'HTT. The combustor temperature, pressure, and fuel equivalence ratio for these cases are given in table 1. The mole fraction of water vapor formed in the combustor for each case is also listed. The conditions for case 1 were established by selecting a combustor pressure of 50 bars and an equivalence ratio that gave a flame temperature of 2000 K. An arbitrary heat loss from the combustor was included by selecting a stagnation temperature that was 100 K less than the flame temperature, that is, 1900 K. Conditions for case 2 were obtained likewise but for a pressure of 250 bars. Conditions for case 3 and case 4 were obtained in a similar fashion but for a temperature of 1600 K. Conditions for case 5 were obtained for $T_o = 1900$ K and $p_o = 250$ bars, the same as for case 2, but for additional oxygen and an equivalence ratio that yielded a mole fraction of 0.21 for O_2 in the test stream. Note that the mole fraction of water vapor in the combustor is 0.154 for cases 1 and 2, 0.122 for cases 3 and 4, and 0.156 for case 5. The values used for the coefficients q_c , α , α_c , β , and J_{min} are also indicated in table 1.

The nozzle contour of the 8'HTT was used to define the variation of the cross-sectional area along the nozzle. Tabulated values of selected wall coordinates r_w and computed boundary-layer-displacement thicknesses δ^* are tabulated in table 2. The numerical values of δ^* were computed from a modified version of the boundary-layer scheme presented in reference 9. The inviscid nozzle contour that was used for the quasi-one-dimensional computation was obtained by subtracting δ^* from r_w at each location of x listed in table 2. A spline fitting scheme for intermediate locations was applied.

The computed results for case 1 with $T_o = 1900$ K, $p_o = 50$ bars, and $\phi = 0.798$ are shown in figure 2. Figure 2(a) shows the difference between saturation temperature and the gas temperature $T_s(p_1) - T_G$, the nucleation rate J , and the mass fraction of liquid water formed. The temperature difference $T_s(p_1) - T_G$ is a measure of the degree of supercooling and provides the driving force for nucleation and droplet growth. The test gas first becomes saturated with respect to water vapor when $T_s(p_1) = T_G$. This occurs at a nozzle location just beyond $x = 6.5$ m. The temperature difference $T_s(p_1) - T_G$ then increases to a maximum value of about 45 K at approximately $x = 12$ m after which $T_s(p_1) - T_G$ decreases rapidly. Figure 2(a) also shows that the nucleation rate J rises exponentially and then decreases rapidly as $T_s(p_1) - T_G$ decreases. The mass fraction of liquid water begins to be significant at about the point of the maximum nucleation rate. The liquid water then continues to increase to the end of the nozzle.

The formation of liquid water under these conditions results in entropy production as shown in figure 2(b). The flow is isentropic until liquid water is formed. The rather rapid formation of liquid water initially causes a correspondingly rapid increase in entropy followed by a more gradual increase as the rate of liquid water formation decreases. This trend is to be expected from equation (83).

The entropy production due to liquid water formation affects the static pressure distribution along the nozzle as shown in figure 2(c). The dashed curve indicates the pressure distribution for an isentropic expansion if no liquid water was formed. The solid curve represents the computation that takes into account nucleation and droplet growth. Note that the process follows the isentropic (dashed) curve to just beyond a nozzle location of $x = 12$ m. At this point the static pressure decreases less rapidly than indicated by the isentropic process. The pressure then increases somewhat to a maximum value after which it decreases in parallel to the isentropic curve. This departure from the isentropic pressure distribution is

due to the transfer of heat to the gaseous phase from the liquid droplets. At the nozzle exit the static pressure for case 1 with condensation is approximately 25 percent larger than that computed for isentropic flow without condensation.

The growth history of the liquid droplets is shown in figure 2(d). The single curve labeled r_* is the critical droplet radius computed from equation (59). Droplets that are larger than r_* grow, whereas those less than r_* evaporate. The series of curves indicates the growth of the sets of droplets that were initially formed at successive stations along the nozzle. Droplet sets that are formed but eventually evaporate are also shown. Only a portion of the numerous sets of droplets formed is included in figure 2(d).

The computed results for case 2 are given in figure 3 and are also for $T_o = 1900$ K but at a higher pressure of $p_o = 250$ bars. Figure 3(a) shows that $T_s(p_1) - T_G$ increases earlier and more rapidly for $p_o = 250$ bars than shown in figure 2(a) for $p_o = 50$ bars. Case 2 shows a slightly lower maximum value of $T_s(p_1) - T_G$ and also an earlier and more rapid decrease in $T_s(p_1) - T_G$ along the nozzle. The nucleation process also begins further upstream for the higher pressure case and displays a more rapid increase and decay. The maximum nucleation rate also achieves a higher value for the higher pressure case. Note also that liquid water forms earlier and more rapidly for $p_o = 250$ bars compared with $p_o = 50$ bars. The total amount of liquid water formed for the higher pressure case is approximately 60 percent more than for case 1.

Figure 3(b) shows the entropy production for case 2. A comparison with figure 2(b) shows that the entropy rises more rapidly for the higher pressure case. This is due to the more rapid formation of liquid water. The entropy also attains a nearly level value, but the total entropy increase is less for $p_o = 250$ bars than for $p_o = 50$ bars. This smaller entropy increase is a direct result of the earlier collapse of the supercooling.

The static pressure distribution along the nozzle for case 2 is shown in figure 3(c). A comparison of figure 3(c) with figure 2(c) shows that the higher pressure case results in an earlier and more pronounced departure from an isentropic process. The static pressure at the nozzle exit for case 2 with condensation is approximately 33 percent larger than that computed for isentropic flow without condensation.

The droplet growth history for case 2 is shown in figure 3(d). The results are similar to case 1 except the liquid droplets form earlier, grow more rapidly, and attain larger sizes.

The results from case 3 are included to indicate the effect of a lower temperature and are

presented in figure 4. A comparison of these results for $T_o = 1600$ K with those for case 1 with $T_o = 1900$ K shows that the lower temperature case results in an earlier onset of nucleation and condensation. More liquid water is formed even though the total water vapor initially present in the test gas is less for case 3 than for case 1. The static pressure distribution plotted in figure 4(c) for case 3 shows a more pronounced departure from an isentropic process than was noted for either case 1 or case 2. The static pressure at the nozzle exit computed for flow with condensation is approximately 57 percent greater than that computed for isentropic flow without condensation as shown in figure 4(c). The results for case 4 with $T_o = 1600$ K, $p_o = 250$ bars, and $\phi = 0.62$ are presented in figure 5 and can be compared with the other cases. The results for case 5, which are for additional oxygen to give a test stream containing 0.21 mole fraction of O_2 , are presented in figure 6. A comparison of these results with case 2 (fig. 3), which is also for 1900 K and 250 bars, shows very little difference. The somewhat different composition of the combustion products produces an expansion that gives a water vapor saturation point for case 5 that is slightly downstream of that for case 2. All the curves shown in figure 6 for case 5 are therefore shifted slightly downstream relative to case 2.

The purpose of presenting these five cases is to show a set of results that indicates the magnitude and the general trends for the effects of water condensation in the Langley 8'HTT. The numerical values used for the coefficients $q_c = 1$, $\alpha = 8$, and $\beta = 2$ are those suggested by Young for pure steam. The value of $\alpha_c = 1$ was used to account for the non-condensable carrier gas. Computations with values of $\alpha_c < 1$ were also carried out but are not included, and they give similar but less pronounced results. The value of J_{min} used was adjusted until a smaller

value had no effect. More appropriate values of the empirical coefficients α , α_c , and β might be determined from experimental data. These data would include static pressure distributions along the nozzle and water droplet size and concentration measurements for supersonic expanding flow of combustion products.

Concluding Remarks

An analysis and numerical scheme has been developed to treat the supersonic expansion of combustion products that takes into account nucleation and finite-rate growth of liquid water droplets. The scheme has two limitations: the flow is assumed to be quasi-one-dimensional and empirical coefficients are required. This analysis has specific application to the computation of flow properties in combustion-heated wind tunnels such as the Langley 8-Foot High-Temperature Tunnel (8'HTT).

Sample computations included in this paper are based on the nozzle contour of the Langley 8'HTT. The numerical values used for the empirical coefficients in these calculations are those suggested by Young for pure steam. The results indicate that the free-stream static pressure can be significantly greater than that computed for isentropic nozzle flow without condensation. The computed entropy production also indicates a loss in total pressure relative to isentropic flow. These computed results suggest that this scheme can be used as a tool to interpret the calibration and flow measurements in combustion-heated wind tunnels. A calibration of combustion-heated wind tunnels must take the effects of water condensation into account.

NASA Langley Research Center
Hampton, VA 23665-5225
July 29, 1988

Appendix A

Extension of Young's Droplet Growth Equations To Include Carrier Gas

This appendix extends the droplet growth equations given by Young in references 3 and 4 for pure steam to the case of water vapor in the presence of a carrier gas. The carrier gas takes into account the noncondensable gases contained in the products of combustion. The equations for mass and heat transfer given by Young for water vapor are used and the appropriate equations for a carrier gas are introduced.

Young's analysis begins by writing the equations for the free molecular transport regime and for the continuum transport regime and then combines these equations to find droplet growth equations that apply to the intermediate regime. Young postulates that the transport processes can be described by free molecular transport from the droplet surface out to a distance of a few mean free paths and by continuum transport beyond. The interface between these two regimes is taken to be at $r + \beta\tilde{\ell}$ where β is a parameter of the order of unity. Young has chosen a value of $\beta = 2$. At this interface the pressure and temperature are denoted by p_i and T_i .

Free Molecular Transport Regime ($\text{Kn} \gg 1$)

The mass transfer equation for water in the free molecular regime from the droplet surface out to the interface given by Young is

$$\frac{dM}{dt} = \frac{2q_c}{2 - q_c} 4\pi r^2 \left[\frac{p_{1,i}}{\sqrt{2\pi\bar{R}_1 T_i}} - \frac{q_c}{q_c} \frac{p_s(T_L, r)}{\sqrt{2\pi\bar{R}_1 T_L}} \right] \quad (\text{A1})$$

and the energy transfer equation in this regime is

$$\left(L \frac{dM}{dt} \right)_1 = 4\pi r^2 \frac{p_{1,i}}{\sqrt{2\pi\bar{R}_1 T_i}} \frac{\gamma_1 + 1}{2\gamma_1} c_{p,1} (T_L - T_i) \quad (\text{A2})$$

The mass transfer equation is appropriate as it stands with $p_{1,i}$ representing the partial pressure of water vapor at the interface and $\bar{R}_1 = R/W_1$. Equation (A2), however, includes only the energy transfer due to water. An additional equation is required to account for the parallel energy transfer due to the carrier gas. The equation for the energy transfer due to the carrier gas has the same form as equation (A2); that is,

$$\left(L \frac{dM}{dt} \right)_c = 4\pi r^2 \frac{p_{c,i}}{\sqrt{2\pi\bar{R}_c T_i}} \frac{\gamma_c + 1}{2\gamma_c} c_{p,c} \alpha_c (T_L - T_i) \quad (\text{A3})$$

where $p_{c,i}$ is the partial pressure of the carrier gas at the interface, $\bar{R}_c = R/W_c$, and α_c is the thermal accommodation coefficient for the interaction between the carrier gas and a water droplet. It should be noted that the thermal accommodation coefficient for water vapor with a water droplet was assumed to be unity by Young as is implied by equation (A2). The total energy transfer in the free molecular regime due to both water vapor and carrier gas is then the sum of equations (A2) and (A3); that is,

$$L \frac{dM}{dt} = 4\pi r^2 \frac{p_i}{\sqrt{2\pi\bar{R}_i T_i}} \frac{\gamma_1 + 1}{2\gamma_1} c_{p,1} (T_L - T_i) f \quad (\text{A4})$$

where

$$f = y_1 \left(\frac{m_1}{m} \right)^{1/2} + (1 - y_1) \left(\frac{m_c}{m} \right)^{1/2} \left[\frac{(\gamma_c + 1)\gamma_1 c_{p,c}}{(\gamma_1 + 1)\gamma_c c_{p,1}} \right] \alpha_c \quad (\text{A5})$$

This expression for f is equation (74). Note that f reduces to unity for the pure steam case.

Continuum Transport Regime ($\text{Kn} \ll 1$)

Young points out that even when the condensation rate is high, the pressure drop beyond the interface due to bulk flow of water vapor towards the droplet is negligible so that

$$p_i = p \quad (\text{A6})$$

The energy transfer equation in the continuum regime given by Young is

$$L \frac{dM}{dt} = 4\pi(r + \beta\tilde{\ell})^2 \frac{\lambda}{r + \beta\tilde{\ell}} (T_i - T_G) \quad (\text{A7})$$

Equation (A6) can be used as it stands and so can equation (A7) if λ is taken to be the thermal conductivity of the gas mixture.

Intermediate Regime

The mass transfer equation in the intermediate regime is obtained by combining equations (A1) and (A6); that is,

$$\frac{dM}{dt} = \frac{2q_c}{2 - q_c} 4\pi r^2 \left[\frac{p_1}{\sqrt{2\pi\bar{R}_1 T_i}} - \frac{q_c}{q_c} \frac{p_s(T_L, r)}{\sqrt{2\pi\bar{R}_1 T_L}} \right] \quad (\text{A8})$$

The energy transfer equation in the intermediate regime can be developed by replacing p_i in equation (A4) with p and combining that result with

equation (A7) to obtain

$$L \frac{dM}{dt} = \frac{4\pi r^2 (\lambda/r) (T_L - T_G)}{r \left[\frac{1}{r + \beta \ell} + \frac{\lambda \sqrt{2\pi R T_i}}{r^2 p} \frac{2\gamma_1}{\gamma_1 + 1} \frac{1}{c_{p,1} f} \right]} \quad (\text{A9})$$

Now if equation (68) is used to eliminate p and equations (69) and (70) are used for Pr and Kn , it follows that

$$L \frac{dM}{dt} = \frac{4\pi r^2 (\lambda/r) (T_L - T_G)}{\left[\frac{1}{1 + 2\beta \text{Kn}} + \frac{\xi (\text{Kn}/\text{Pr}) \sqrt{T_i/T_G}}{f} \right]} \quad (\text{A10a})$$

and with the additional approximation that $\sqrt{T_i/T_G}$ can be taken as unity,

$$L \frac{dM}{dt} = \frac{4\pi r^2 (\lambda/r) (T_L - T_G)}{\left[\frac{1}{1 + 2\beta \text{Kn}} + \frac{\xi (\text{Kn}/\text{Pr})}{f} \right]} \quad (\text{A10b})$$

where

$$\xi = \frac{\sqrt{8\pi}}{1.5} \frac{2\gamma_1}{\gamma_1 + 1} \quad (\text{A11})$$

Young continues his analysis by developing a relationship between $T_L - T_G$ and $T_s(p_1) - T_G$. First,

$$(T_L - T_G) = [T_s(p_1) - T_G] - (T'_s - T_L) + [T'_s - T_s(p_1)] \quad (\text{A12})$$

where T'_s is the saturation temperature that corresponds to $p_s(T_L, r)$. Young states that a very good approximation to the second term is

$$(T'_s - T_L) = \frac{r^*}{r} [T_s(p_1) - T_G] \quad (\text{A13})$$

The third term, $T'_s - T_s(p_1)$, is obtained in the following way. Equation (A4) with $p_i = p$ and equation (A8) are used to eliminate dM/dt to obtain an expression for $p_s(T_L, r)/p_1$; that is,

$$\frac{p_s(T_L, r)}{p_1} = \frac{q_c}{q_e} \sqrt{\frac{T_L}{T_i}} \left[1 - \frac{2 - q_c}{2q_c} \frac{\gamma_1 + 1}{2\gamma_1} \frac{c_{p,1}}{L} \times (T_L - T_i) \frac{f}{y_1} \left(\frac{m}{m_1} \right)^{1/2} \right] \quad (\text{A14})$$

Young then uses an approximate integral form of the Clausius-Clapeyron equation,

$$T'_s - T_s(p_1) = \frac{\bar{R}_1 [T_s(p_1)]^2}{L} \ln \frac{p_s(T_L, r)}{p_1} \quad (\text{A15})$$

An expression for $T_L - T_i$ in equation (A14) can be obtained by equating equation (A4) with $p_i = p$ to equation (A10a) to get

$$T_L - T_i = \delta (T_L - T_G) \quad (\text{A16})$$

where

$$\delta = \frac{\xi \text{Kn}/\text{Pr}}{\frac{f \sqrt{T_G/T_i}}{1 + 2\beta \text{Kn}} + \frac{\xi \text{Kn}}{\text{Pr}}} \quad (\text{A17a})$$

The additional approximation used by Young that $\sqrt{T_G/T_i}$ is unity leads to

$$\delta = \frac{\xi \text{Kn}/\text{Pr}}{\frac{f}{1 + 2\beta \text{Kn}} + \frac{\xi \text{Kn}}{\text{Pr}}} \quad (\text{A17b})$$

which is equation (82). Young also postulates that

$$\frac{q_c}{q_e} = 1 + \frac{\alpha (T_L - T_i)}{T_s(p_1)} + \dots \quad (\text{A18})$$

where α is a constant and higher order terms are neglected. Also note that

$$\sqrt{\frac{T_L}{T_i}} = \left(\frac{T_L - T_i}{T_i} + 1 \right)^{1/2} \quad (\text{A19})$$

Substituting equations (A18) and (A19) into equation (A14), taking the logarithm of both sides of the resulting equation, and then using the approximation $\ln(1 + x) = x$ for $x \ll 1$ yield

$$\ln \frac{p_s(T_L, r)}{p_1} = \frac{\alpha (T_L - T_i)}{T_s(p_1)} + \frac{\frac{1}{2} (T_L - T_i)}{T_i} - \frac{2 - q_c}{2q_c} \frac{\gamma_1 + 1}{2\gamma_1} \times \frac{c_{p,1}}{L} (T_L - T_i) \frac{f}{y_1} \left(\frac{m}{m_1} \right)^{1/2} \quad (\text{A20})$$

Substituting this expression into equation (A15) and using equation (A16) give

$$T'_s - T_s(p_1) = \nu \delta (T_L - T_G) \quad (\text{A21})$$

where

$$\nu = \frac{\bar{R}_1 T_s(p_1)}{L} \left[\alpha + \frac{1}{2} \frac{T_s(p_1)}{T_i} - \frac{2 - q_c}{2q_c} \frac{\gamma_1 + 1}{2\gamma_1} \times \frac{c_{p,1} T_s(p_1)}{L} \frac{f}{y_1} \left(\frac{m}{m_1} \right)^{1/2} \right] \quad (\text{A22a})$$

The additional approximation that $T_s(p_1)/T_i$ is unity leads to

$$\nu = \frac{\bar{R}_1 T_s(p_1)}{L} \left[\alpha + \frac{1}{2} - \frac{2 - q_c}{2q_c} \frac{\gamma_1 + 1}{2\gamma_1} \frac{c_{p,1} T_s(p_1)}{L} \right. \\ \left. \times \frac{f}{y_1} \left(\frac{m}{m_1} \right)^{1/2} \right] \quad (\text{A22b})$$

which is equation (78). A relationship between $(T_L - T_G)$ and $[T_s(p_1) - T_G]$ can now be formed by using equations (A13) and (A21) in equation (A12) to obtain

$$(T_L - T_G) = \frac{1 - r_*/r}{1 - \nu\delta} [T_s(p_1) - T_G] \quad (\text{A23})$$

This expression for $T_L - T_G$ can be substituted into equation (A10b) and since the mass of a liquid water droplet is

$$M = \frac{4}{3} \pi r^3 \rho_L \quad (\text{A24})$$

the droplet growth equation becomes

$$\frac{dr}{dt} = \frac{\lambda(1 - r_*/r)[T_s(p_1) - T_G]}{(L\rho_L r) \left[\frac{1}{1 + 2\beta\text{Kn}} + \frac{\xi(\text{Kn}/\text{Pr})(1 - \nu)}{f} \right]} \quad (\text{A25})$$

This equation reduces to that given by Young for pure steam for $f = 1$.

For droplets with $z = \frac{r}{r_*} \geq 1.1$, Young defines a Knudsen number based on a critical droplet radius as

$$\text{Kn}_* = \frac{\tilde{\ell}}{2r_*} \quad (\text{A26})$$

and assumes that the vapor properties remain constant over an integration step so that equation (A25)

can be written as

$$\frac{dz}{dt} = \frac{\lambda(1 - 1/z)[T_s(p_1) - T_G]}{L\rho_L r_*^2 \left[\frac{z^2}{z + 2\beta\text{Kn}_*} + \frac{\xi(\text{Kn}_*/\text{Pr})(1 - \nu)}{f} \right]} \quad (\text{A27})$$

This equation can be integrated over a time step Δt from z_j to z_{j+1} to give equation (72) where the terms Ω , f , θ , Λ , ξ , and ν are defined by equations (73) through (78).

For droplets with $r/r_* < 1.1$, Young uses the energy transfer equation appropriate in the free molecular regime; that is, equation (A4) with $p_i = p$ and $T_i = T_G$. Again if equation (A23) but with $\delta = 1$ and equation (A24) are used, it follows that for $\frac{r}{r_*} < 1.1$,

$$\frac{dr}{dt} = \frac{p}{\rho_L L \sqrt{2\pi \bar{R} T_G}} \frac{\gamma_1 + 1}{2\gamma_1} c_{p,1} \frac{1 - r_*/r}{1 - \nu} [T_s(p_1) - T_G] f \quad (\text{A28})$$

Now define

$$\psi = \frac{p}{r \sqrt{2\pi \bar{R} T_G}} \left(\frac{\gamma_1 + 1}{2\gamma_1} \right) \frac{c_{p,1}}{L\rho_L} \frac{1}{1 - \nu} [T_s(p_1) - T_G] f \quad (\text{A29})$$

so that

$$\frac{dr}{dt} = r\psi \left(1 - \frac{r_*}{r} \right) \quad (\text{A30})$$

Subtraction of dr_*/dt from both sides of this equation gives

$$\frac{d(r - r_*)}{dt} = \psi(r - r_*) - \frac{dr_*}{dt} \quad (\text{A31})$$

At this point, Young makes the approximation that ψ is constant over an integration step so that equation (A31) can be integrated over a time interval Δt to give equation (79). An expression for ψ given by equation (80) is obtained from equation (A29) with r set equal to r_j , and all other quantities in the expression for ψ are also evaluated at station j .

Appendix B

Thermodynamic and Transport Property Data for Products of Combustion

This appendix lists a set of coefficients from which thermodynamic and transport properties can be computed for products of combustion. The thermodynamic properties can be computed over the temperature range from 200 K to 3000 K and the transport properties up to 500 K. The coefficients for the thermodynamic properties were obtained from a least-squares fit to tabulated heat capacity and equilibrium constant values given in the JANAF Thermochemical Tables (ref. 10). The coefficients for computing viscosity were determined from a least-squares

fit to tabulated data presented by Touloukian, Saxena, and Hestermans (ref. 7) and the coefficients for computing thermal conductivity using tabulated data presented by Touloukian, Liley, and Saxena (ref. 8).

Table B1 lists coefficients $A_{n,k}$ ($n = 1, 2, \dots, 6$) that appear in equation (36) for the heat capacity, the integration constant for the enthalpy $A_{7,k}$ that appears in equation (42), and the integration constant for the entropy $A_{8,k}$ that appears in equation (44). The numerical values listed correspond to units for $C_{p,k}$ in calories per mol-kelvin. The coefficients listed in table B1(a) apply to a temperature range of $200 \text{ K} \leq T \leq 1000 \text{ K}$ and table B1(b) apply to $1000 \text{ K} \leq T \leq 3000 \text{ K}$.

Table B1. Heat Capacity Coefficients $A_{n,k}$ ($n = 1, 2, \dots, 6$) and Constants of Integration for Enthalpy $A_{7,k}$ and Entropy $A_{8,k}$

k	A _{n,k} for n =						A _{7,k}	A _{8,k}
	1	2	3	4	5	6		
(a) 200 K ≤ T ≤ 1000 K								
1	6.41000E+01	7.59151E+00	-8.41829E-04	6.68750E-06	-5.19580E-09	1.55769E-12	-6.04359E+04	2.06410E+00
2	1.04750E+02	3.37574E+00	2.38924E-02	-2.68777E-05	1.71801E-08	-4.69551E-12	-9.65120E+04	2.61229E+01
3	-1.60500E+02	9.06284E+00	-9.91073E-03	1.97943E-05	-1.49575E-08	4.10256E-12	-2.79118E+04	-2.76320E+00
4	4.94000E+01	6.94324E+00	-3.59602E-03	1.51603E-05	-1.54277E-08	5.20513E-12	-2.29792E+03	1.01347E+01
5	-4.26900E+02	9.83533E+00	-7.22941E-03	8.48001E-06	-4.45280E-09	1.01282E-12	-2.44860E+02	-2.44460E+01
6	-1.51550E+02	8.84079E+00	-8.29361E-03	1.52780E-05	-1.03811E-08	2.52244E-12	-1.51928E+03	-3.22920E+00
7	0	4.96800E+00	0	0	0	0	5.06219E+04	-9.14000E-01
8	1.06200E+02	5.01442E+00	-8.54283E-04	1.74321E-06	-1.46562E-09	4.55128E-13	5.74789E+04	1.04430E+01
9	1.65300E+02	6.18389E+00	2.60375E-03	-5.47821E-06	5.88287E-09	-2.02564E-12	6.45433E+03	8.62130E+00
10	-9.10512E+00	8.49215E+00	-9.77414E-03	2.32087E-05	-1.98449E-08	6.05054E-12	1.93658E+04	3.97820E+00
(b) 1000 K ≤ T ≤ 3000 K								
1	3.49199E+03	-4.64184E+00	1.68818E-02	-7.39530E-06	1.68507E-09	-1.58341E-13	-7.74261E+04	7.74501E+01
2	-2.22684E+03	1.37397E+01	2.55399E-03	-1.42507E-06	3.76285E-10	-3.87790E-14	-8.53153E+04	-3.47509E+01
3	-3.58341E+02	6.31771E+00	3.26443E-03	-1.66622E-06	4.13442E-10	-4.03866E-14	-2.62483E+04	9.46980E+00
4	-1.53922E+03	1.07380E+01	-1.38694E-03	5.81156E-07	-5.58070E-11	-3.28450E-15	5.83496E+03	-1.64089E+01
5	1.48203E+03	2.67165E+00	3.89978E-03	-9.04231E-07	6.54370E-11	4.63902E-15	-9.63201E+03	1.92568E+01
6	5.22642E+02	3.50182E+00	6.39254E-03	-3.40202E-06	8.93124E-10	-9.30231E-14	-4.24934E+03	2.58749E+01
7	0	4.96800E+00	0	0	0	0	5.06219E+04	-9.14000E-01
8	8.12266E+01	4.87159E+00	7.49130E-05	-3.65807E-08	7.95819E-12	-1.04187E-16	5.76456E+04	1.09880E+01
9	1.94043E+03	5.88669E-01	7.14722E-03	-2.90201E-06	6.10537E-10	-5.27109E-14	-2.41961E+03	4.44795E+01
10	-3.78024E+02	6.62079E+00	3.29444E-03	-1.87396E-06	5.15206E-10	-5.54624E-14	2.17433E+04	1.07487E+01

Table B2 lists coefficients $B_{n,j}$ that appear in equation (35) for the six equilibrium constants $K_{p,j}$ that correspond to reactions I through VI (eqs. (25)

through (30)). The numerical values of $B_{n,j}$ listed correspond to units for $K_{p,j}$ that are nondimensional for $j = 1, 3$, and 6 and are in atmospheres for $j = 2, 4$, and 5.

Table B2. Equilibrium Constant Coefficients $B_{n,j}$

j	$B_{n,j}$ for $n =$					
	1	2	3	4	5	6
1	5.09440E+03	-5.98336E+00	1.65031E-03	-4.45924E-07	4.89037E-11	8.42816E-16
2	6.80400E+04	-2.02038E+01	-2.04607E-03	1.83617E-06	-6.39945E-10	8.33955E-14
3	-5.22510E+04	1.04345E+01	3.07030E-03	-1.40641E-06	3.75299E-10	-4.25248E-14
4	-5.97702E+04	1.26601E+01	3.26442E-03	-1.76622E-06	5.10028E-10	-5.95591E-14
5	-9.40571E+03	3.89944E+00	3.06797E-05	-2.40321E-07	1.01593E-10	-1.35585E-14
6	-2.10521E+04	8.66294E-01	2.64558E-03	-1.57780E-06	4.66330E-10	-5.46540E-14

Table B3 lists coefficients $D_{n,k}$ that appear in equation (63) for the viscosity of the seven species with $k = 1, 2, \dots, 6, 10$. The units for μ_k based on this set of coefficients are newtons-second per meter². Table B4 lists coefficients $E_{n,k}$ in equation (66) for the thermal conductivity of the seven species with $k = 1, 2, \dots, 6, 10$. The units for λ_k based on

this set of coefficients are joules per second-meter-kelvin. Note that the viscosity and thermal conductivity data are only required in the region where water droplet growth occurs, which is generally at a temperature less than 500 K. Also, at these temperatures the species corresponding to $k = 7, 8$, and 9 do not appear in significant amounts.

Table B3. Coefficients in Expression for Viscosity $D_{n,k}$

k	$D_{n,k}$ for $n =$			
	1	2	3	4
1	-1.5371E-05	1.5429E-07	-3.1981E-10	2.7958E-13
2	-2.5212E-07	5.5024E-08	-1.2381E-11	-5.5279E-15
3	-4.9877E-07	7.8689E-08	-6.9794E-11	3.6438E-14
4	-5.7709E-07	8.8852E-08	-7.0382E-11	3.4305E-14
5	1.6225E-06	2.9338E-08	-1.9878E-11	1.1391E-14
6	-6.0917E-08	7.6311E-08	-6.4962E-11	3.2374E-14
10	-8.4886E-07	8.5390E-08	-7.1595E-11	3.5702E-14

Table B4. Coefficients in Expression for Thermal Conductivity $E_{n,k}$

k	$E_{n,k}$ for $n =$			
	1	2	3	4
1	-2.0450E-01	1.7566E-03	-4.6279E-06	4.2102E-09
2	-1.4403E-05	2.5166E-05	1.3405E-07	-1.1069E-10
3	5.3712E-04	8.8425E-05	-1.5431E-08	-1.8246E-11
4	-3.8505E-03	1.3168E-04	-1.2385E-07	8.1162E-11
5	-5.5274E-02	1.2443E-03	-1.9310E-06	1.3762E-09
6	-3.0706E-03	1.3215E-04	-1.4900E-07	1.0324E-10
10	-1.8772E-03	1.1087E-04	-6.9710E-08	2.7900E-11

Appendix C

Computer Program

This appendix presents a computer program, FIRACON, which has been developed to solve the finite-rate condensation problem with the solution technique of the present paper. The program is

written in FORTRAN Version 5 language for the CDC® CYBER 180 series digital computer system, model 860, with Network Operating System. The program requires approximately 134000 octal locations of core language and a typical case requires approximately 200 central processing unit seconds. Program input requirements and operating instructions are summarized in the program.

```

1      PROGRAM FIRACON(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,
2      1 SAVDAT,TAPE7=SAVDAT,RDIST,TAPE33=RDIST)
3      C*****
4      C
5      C      F I N I T E   R A T E   C O N D E N S A T I O N
6      C
7      C*****
8      C
9      C      PROGRAM FIRACON PROVIDES A NUMERICAL SOLUTION FOR THE
10     C      ADIABATIC EXPANSION OF COMBUSTION PRODUCTS WITH NUCLEATION
11     C      AND WATER DROPLET GROWTH. THE NUMERICAL SOLUTION IS
12     C      DIVIDED INTO THREE SUCCESSIVE PARTS. THE FIRST PART
13     C      INCLUDES THE COMPUTATION OF THE STAGNATION CONDITIONS
14     C      IN THE COMBUSTION CHAMBER AND THE DETERMINATION OF THE
15     C      MASS FLOW RATE. THE SECOND PART INVOLVES THE COMPUTATION
16     C      OF ISENTROPIC FLOW FROM THE NOZZLE THROAT TO A POINT IN
17     C      THE NOZZLE WHERE NUCLEATION JUST BEGINS. THE THIRD PART
18     C      DEALS WITH THE COMPUTATION OF THE NUCLEATION PROCESS
19     C      TO DETERMINE THE NUMBER OF DROPLETS FORMED AND THE
20     C      SUBSEQUENT GROWTH OF THE LIQUID WATER DROPLETS.
21     C
22     C      COMMON BLOCKS ARE USED EXTENSIVELY TO PASS INFORMATION
23     C      BETWEEN THE VARIOUS SUBPROGRAMS. THE CONTENTS OF THE
24     C      PRIMARY COMMON BLOCKS (PARTICULARLY AS THEY RELATE TO
25     C      INPUT DATA AND OPERATING INSTRUCTIONS) ARE DESCRIBED
26     C      IN THE DATA INPUT AND INITIALIZATION SUBROUTINE, DATAII.
27     C
28     C      THE USE OF COMMON BLOCKS IS SUMMARIZED IN THE FOLLOWING
29     C      TABLE:
30     C
31     C
32     C      COMMON BLOCK
33     C      SUBPROGRAM  A B C D E F G H I J K L M N O P Q R S T U V W X Y
34     C      FIRACON
35     C      AVSX          X              X                      X   X
36     C      CCP          X X              X
37     C      CDEN          X X              X
38     C      CECOMP        X   X          X X          X X X   X
39     C      CEDATA        X              X
40     C      CHG          X X              X

```

```

41 C          CS          X X          X
42 C      DATAI      X X      X      X X      X      X      X      X
43 C      DBLIT      X          X          X          X          X          X
44 C      ELEMBA      X          X          X          X          X          X
45 C      EXPP
46 C      FITLAM
47 C      FITMU
48 C      FTEMP      X          X      X      X          X          X
49 C      GRL      X          X      X      X          X          X      X
50 C      GRLPRP      X          X      X      X      X      X          X      X
51 C      GRS      X          X      X          X          X          X
52 C      KPJ
53 C      MIXLAM
54 C      MIXMU
55 C      NUCRAT      X          X
56 C      PART1      X      X      X          X      X      X      X      X
57 C      PART2      X      X      X      X          X      X      X      X
58 C      PART3      X      X      X      X      X      X      X      X
59 C      PLTOUT      X      X      X      X          X      X      X      X
60 C      PRTOU      X      X      X      X      X      X      X      X
61 C      SATTEM      X
62 C      XVSA      X      X          X
63 C
64 C      WHERE THE COLUMN HEADINGS REFER TO THE FOLLOWING
65 C      COMMON BLOCKS:
66 C
67 C      A) /ADJUST/      H) /CONSTS/      N) /K1K2ETC/      T) /SIGCOM/
68 C      B) /ARECOM/      I) /EQCOM/      O) /OUT1/      U) /SIGMAS/
69 C      C) /CMOUT1/      J) /EXPDAT/      P) /OUT2/      V) /SVX2/
70 C      D) /CMOUT2/      K) /FEED/      Q) /PLTBLK/      W) /SWITCH/
71 C      E) /CMOUT3/      L) /GAMOUT/      R) /PLTOUT/      X) /TANOP/
72 C      F) /COEFCU/      M) /INPT/      S) /RESLTS/      Y) //
73 C      G) /CONST/
74 C
75 C      COMMON/SWITCH/SWEND,SWPO,SWG0
76 C      INTEGER SWEND,SWPO,SWG0
77 C      COMMON DUMMY(1000Z)
78 C
79 C      CALL PSEUDO
80 C      CALL LEROY
81 C      CALL CALPLT(4.5,1.5,-3)
82 C      10 CONTINUE
83 C      CALL DATAI
84 C      IF(SWEND.EQ.1) GO TO 20
85 C      CALL PART1
86 C      CALL PART2
87 C      CALL PART3
88 C      IF(SWG0.EQ.1) CALL PLTOUT
89 C      GO TO 10
90 C      20 CONTINUE
91 C      CALL CALPLT(0.,0.,999)
92 C      STOP
93 C      END

```

```

1      SUBROUTINE AVSX(X,A)
2      C
3      C      SUBROUTINE AVSX CALCULATES THE NOZZLE AREA AS A
4      C      FUNCTION OF X POSITION.
5      C      ACOEF CONTAINS THE SPLINE COEFFICIENTS DETERMINED
6      C      BY THE LIBRARY ROUTINE CSDS
7      C
8      COMMON/ARECOM/NA,XA,ACDEF
9      COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
10     REAL K,M1
11     DIMENSION ACOEF(10,4)
12     DIMENSION XA(10)
13     C
14     NPD = NA-1
15     XXI = X
16     DO 10 IJ=1,NPD
17     IF(XA(IJ).LE.XXI.AND.XXI.LE.XA(IJ+1)) GO TO 20
18     CONTINUE
19     IJ = NPD
20     H = XXI - XA(IJ)
21     RBARX = ((ACDEF(IJ,4)*H + ACDEF(IJ,3))*H
22     1 + ACDEF(IJ,2))*H + ACDEF(IJ,1)
23     A = PI*RBARX**2
24     RETURN
25     END

```

```

1      SUBROUTINE CCP(T,CP,CPI,CPC)
2      C
3      C      SUBROUTINE CCP CALCULATES THE SPECIFIC HEAT CAPACITY FOR WATER
4      C      VAPOR AND THE CARRIER GAS
5      C
6      COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
7      REAL K,M1
8      COMMON/COEFCO/COEF(10,8,2)
9      COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
10     C
11     VAL = 0.
12     J = 1
13     IF(T.LT.1000.) GO TO 10
14     J = 2
15     10 CONTINUE
16     C
17     C      EQUATION (36)
18     C
19     DO 20 I=1,10
20     VAL = VAL + SIGMA(I)*(COEF(I,1,J)/T + COEF(I,2,J)
21     1 + COEF(I,3,J)*T + COEF(I,4,J)*T**2 + COEF(I,5,J)*T**3
22     2 + COEF(I,6,J)*T**4)
23     IF(I.EQ.1) CPI = VAL
24     20 CONTINUE
25     CPC = VAL - CPI
26     C
27     C      EQUATION (38)
28     C
29     CPI = (CPI/SIGMA(1))*4.184/W(1)
30     CPC = (CPC/(SIG - SIGMA(1)))*4.184
31     C
32     C      EQUATION (24)
33     C
34     WC = 0.
35     DO 30 I=2,10
36     WC = WC + SIGMA(I)*W(I)
37     30 CONTINUE
38     WC = WC/(SIG - SIGMA(1))
39     C
40     C      EQUATION (40)
41     C
42     CPC = CPC/WC
43     CP = 4.184*VAL
44     RETURN
45     END

```

```

1      SUBROUTINE CDEN(RHO,S,T)
2      C
3      C      SUBROUTINE CDEN CALCULATES THE MASS DENSITY OF
4      C      THE GASEOUS MIXTURE BY INVERTING EQUATION (44)
5      C
6      COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
7      REAL K,M1
8      COMMON/COEFCO/COEF(10,8,2)
9      COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
10     C
11     VAL = 0.
12     RP = CAPR/4.184
13     J = 1
14     IF(T.LT.1000.) GO TO 10
15     J = 2
16     10 CONTINUE
17     C
18     C      EQUATION (46)
19     C
20     DO 20 I=1,10
21     VAL = VAL + SIGMA(I)*(-COEF(I,1,J)/T + (COEF(I,2,J) - RP)*ALOG(T)
22     1 + COEF(I,3,J)*T + COEF(I,4,J)*T**2/2. + COEF(I,5,J)*T**3/3.
23     2 + COEF(I,6,J)*T**4/4. + COEF(I,8,J))
24     20 CONTINUE
25     VAL = 4.184*VAL
26     C
27     C      EQUATION (45)
28     C
29     VAL = S - VAL
30     VAL = VAL + CAPR*SIG*ALOG(CAPR/PSUPO)
31     DO 30 I=1,10
32     IF(SIGMA(I).EQ.0.) GO TO 30
33     VAL = VAL + CAPR*SIGMA(I)*ALOG(SIGMA(I))
34     30 CONTINUE
35     VAL = -VAL/(CAPR*SIG)
36     RHO = EXPP(VAL)
37     RETURN
38     END

```

```

1      SUBROUTINE CECOMP
2
3      C      SUBROUTINE CECOMP CALCULATES THE CHEMICAL EQUILIBRIUM
4      C      COMPOSITION OF COMBUSTION PRODUCTS
5      C
6      DIMENSION KP(6),BB(6,6)
7      REAL KP,K1,K2,K3,K4,K5,K6
8      REAL KPJ
9      COMMON/K1K2ETC/K1,K2,K3,K4,K5,K6
10     COMMON/SIGMAS/SH,SO,SN,SC
11     COMMON/CONSTS/FACTOR,EPS
12     COMMON/RESLTS/S(11)
13     COMMON/INPT/TO,PO,XLAST,PHI1,RHC,RNO
14     COMMON/TANOP/TXX,PXX
15     COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
16
17     C      EQUILIBRIUM CONSTANT COEFFICIENTS, B(N,J)
18     C      (N=1,2,...,6),(J=1,2,...,6) ... TABLE B2
19     C
20     DATA BB/5.0943976E+3,-5.9833561,1.6503132E-3,
21     1 -4.4592415E-7,4.8903658E-11,8.4281563E-16,6.8040026E+4,
22     2 -2.0203827E+1,-2.0460652E-3,1.8361667E-6,-6.3994532E-10,
23     3 8.3395483E-14,-5.2250958E+4,1.0434537E+1,3.0703042E-3,
24     4 -1.4064069E-6,3.7524859E-10,-4.2524815E-14,
25     5 -5.9770152E+4,1.2660142E+1,3.2644206E-3,-1.7662154E-6,
26     6 5.1002835E-10,-5.9559096E-14,-9.4057111E+3,
27     7 3.8994369,3.0679650E-5,-2.4032069E-7,1.0159289E-10,
28     8 -1.3558463E-14,-2.1052085E+4,8.6629408E-1,2.6455821E-3,
29     9 -1.5777998E-6,4.6632962E-10,-5.4654014E-14/
30     DATA PSUPO/1.01325E+5/
31     DATA FACTOR/0.5/
32     DATA EPS/1.E-8/
33
34     C      EQUATION (35)
35     C
36     C
37     DO 10 J=1,6
38     KP(J) = KPJ(BB(1,J),TXX)
39
40     10 CONTINUE
41     K1 = 1./KP(1)
42     K2 = (PXX/PSUPO)*KP(2)
43     K2 = 1./K2
44     K4 = KP(3)/(PXX/PSUPO)
45     K5 = KP(4)/(PXX/PSUPO)
46     K3 = KP(5)
47     K6 = KP(6)
48     RCO = PHI1/(2.0 + 0.5*RHC)
49     SC = 1000.0/(RHC + 12.0 + (14.0*RNO + 16.0)/RCO)
50     SH = RHC*SC
51     SO = SC/RCO
52     SN = RNO*SO
53     CALL ELENBAL
54     DO 20 I=1,10
55     SIGMA(I) = S(I)
56
57     20 CONTINUE
58     SIG = S(11)
59     RETURN
60     END

```

```

1      BLOCK DATA CEDATA
2
3      C      HEAT CAPACITY COEFFICIENTS A(N,K) (N=1,2,...,6)
4      C      AND CONSTANTS OF INTEGRATION FOR ENTHALPY A(7,K)
5      C      AND ENTROPY A(8,K) ... TABLE B1
6      C      THESE COEFFICIENTS CORRESPOND TO THE SPECIES
7      C      H2O, CO2, CO, O2, H2, N2, H, O, OH, AND NO
8      C      IN THAT ORDER.
9
10     COMMON/COEFCO/COEF(10,8,2)
11     DATA ((COEF(I,J,1),I=1,10),J=1,8)
12     1 /64.100011,104.75008,-1.6049999E+2,49.400013,
13     2 -426.9,-151.54998,0.,106.20001,165.30001,-9.1051247,
14     3 7.5915145,3.3757382,9.0628437,6.9432404,9.8353258,
15     4 8.8407937,4.968,5.0144162,6.1838936,8.4921514,
16     5 -8.4182903E-4,2.3892444E-2,-9.9107277E-3,-3.5960249E-3,
17     6 -7.229411E-3,-8.2936122E-3,0.,-8.5428273E-4,2.6037478E-3,
18     7 -9.7741398E-3,6.6874984E-6,-2.68777E-5,1.9794288E-5,1.5160255E-5,
19     8 8.4800107E-6,1.5277956E-5,0.,1.74321E-6,-5.4782064E-6,
20     9 2.3208705E-5,-5.1958027E-9,1.7180074E-8,-1.4957458E-8,
21     1 -1.5427738E-8,
22     2 -4.4527963E-9,-1.0381117E-8,0.,-1.4656169E-9,5.8828683E-9,
23     3 -1.9844914E-08,
24     4 1.5576918E-12,-4.6955142E-12,4.1025637E-12,5.2051277E-12,
25     5 1.0128202E-12,2.5224354E-12,0.,4.5512793E-13,-2.0256414E-12,
26     6 6.0505371E-12,-60435.85,-96512.03,-27911.82,-2297.92,-244.86,
27     7 -1519.28,50621.94,57478.92,6454.33,19365.80,
28     8 2.0641,26.1229,-2.7632,10.1347,-24.446,
29     9 -3.2292,-C.9140,10.4430,8.6213,3.9782/
30     DATA ((COEF(I,J,2),I=1,10),J=1,8)
31     1 /3491.9931,-2226.8402,-3.5834144E+2,-1539.2227,
32     2 1482.0260,522.64184,0.,81.226626,1940.4339,-3.7802350E+2,
33     3 -4.6418407,13.739656,6.3177058,10.738034,2.6716453,
34     4 3.5018215,4.968,4.8715858,0.58866853,6.6207915,
35     5 1.6881822E-2,2.5539892E-3,3.26443E-03,-1.3869361E-3,
36     6 3.8997751E-3,6.3925364E-3,0.,7.4913043E-5,7.1472198E-3,
37     7 3.2944365E-3,
38     8 -7.3953048E-6,-1.4250656E-6,-1.6662247E-6,5.8115599E-7,
39     9 -9.042312E-7,-3.4020227E-6,0.,-3.658067E-8,-2.902006E-6,
40     1 -1.8739611E-6,
41     2 1.6850683E-9,3.7628479E-10,4.1344159E-10,-5.5807018E-11,
42     3 6.5437004E-11,8.9312396E-10,0.,7.9581929E-12,6.1053683E-10,
43     4 5.1520591E-10,
44     5 -1.583412E-13,-3.8779049E-14,-4.0386589E-14,-3.2845032E-15,
45     6 4.6390234E-15,-9.3023097E-14,0.,-1.0418673E-16,-5.2710918E-14,
46     7 -5.5462447E-14,-77426.11,-85315.28,-26248.25,5834.96,-9632.01,
47     8 -4249.34,50621.94,57645.58,-2419.61,21743.30,
48     9 77.4501,-34.7509,9.4698,-16.4089,19.2568,
49     10 25.8749,-0.9140,10.9880,44.4795,10.7487/
50     END

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

1      SUBROUTINE CHG(T,HG,HG1)
2
3      C      SUBROUTINE CHG CALCULATES THE SPECIFIC ENTHALPY
4      C      OF THE GASEOUS MIXTURE AND OF WATER VAPOR
5
6      COMMON/COEFCO/COEF(10,8,2)
7      COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
8      REAL K,M1
9      COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
10
11      C      VAL = 0.
12      J = 1
13      IF(T.LT.1000.) GO TO 10
14      J = 2
15      10 CONTINUE
16
17      C      EQUATION (42)
18
19      DO 20 I=1,10
20      VAL = VAL + SIGMA(I)*(COEF(I,1,J)*ALOG(T) + COEF(I,2,J)*T
21      1 + COEF(I,3,J)*T**2/2. + COEF(I,4,J)*T**3/3.
22      2 + COEF(I,5,J)*T**4/4. + COEF(I,6,J)*T**5/5. + COEF(I,7,J))
23      IF(I.EQ.1) HG1 = VAL/SIGMA(1)
24      20 CONTINUE
25      HG = 4.184*VAL
26
27      C      EQUATION (43)
28
29      HG1 = HG1*4.184/W(1)
30      RETURN
31      END

```

```

1      SUBROUTINE CS(S,RHO,T)
2
3      C      SUBROUTINE CS CALCULATES THE SPECIFIC ENTROPY
4      C      OF THE GASEOUS MIXTURE
5
6      COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
7      REAL K,M1
8      COMMON/COEFCO/COEF(10,8,2)
9      COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
10
11      C      VAL = 0.
12      RP = CAPR/4.184
13      J = 1
14      IF(T.LT.1000.) GO TO 10
15      J = 2
16      10 CONTINUE
17
18      C      EQUATION (44)
19
20      DO 20 I=1,10
21      VAL = VAL + SIGMA(I)*(-COEF(I,1,J)/T + (COEF(I,2,J) - RP)*ALOG(T)
22      1 + COEF(I,3,J)*T + COEF(I,4,J)*T**2/2. + COEF(I,5,J)*T**3/3.
23      2 + COEF(I,6,J)*T**4/4. + COEF(I,8,J))
24      20 CONTINUE
25      VAL = 4.184*VAL
26      VAL = VAL - CAPR*SIG*ALOG(RHO) - CAPR*SIG*ALOG(CAPR/PSUPO)
27      DO 30 I=1,10
28      IF(SIGMA(I).EQ.0.) GO TO 30
29      VAL = VAL - CAPR*SIGMA(I)*ALOG(SIGMA(I))
30      30 CONTINUE
31      S = VAL
32      RETURN
33      END

```



```

1      SUBROUTINE DATAII
2
3      C      SUBROUTINE DATAII HANDLES THE DATA INPUT AND
4      C      INITIALIZATION. THE SUBROUTINE CSDS IS A PART OF THE
5      C      MATHEMATICAL LIBRARY AT LANGLEY. FOR MORE INFORMATION
6      C      SEE "MATHEMATICAL AND STATISTICAL SOFTWARE AT LANGLEY",
7      C      CENTRAL SCIENTIFIC COMPUTING COMPLEX DOCUMENT N2-3C.
8
9      C      DIMENSION ACOEF(10,4),DY(10),XA(10),RWA(10),DELSTR(10)
10     C      DIMENSION Y(10)
11     C      DIMENSION WK(79)
12
13     C      "EXPDAT" VARIABLES
14
15     C      NEXP  - NUMBER OF EXPERIMENTAL DATA POINTS TO BE
16     C              DISPLAYED ON PRESSURE PLOT. IF NEXP IS
17     C              ZERO, NO EXPERIMENTAL DATA IS PLOTTED.
18     C              IF NEXP IS NOT ZERO, THE EXPERIMENTAL
19     C              DATA IS INCLUDED ON PLOT TYPE 1.
20
21     C      XEXP  - X POSITIONS FOR WHICH EXPERIMENTAL DATA
22     C              IS TO BE DISPLAYED ON PRESSURE PLOT
23
24     C      PEXP  - EXPERIMENTAL VALUES OF PRESSURE TO BE
25     C              DISPLAYED ON PRESSURE PLOT
26
27     C      PREF  - REFERENCE PRESSURE - I.E., THE VALUE PEXP/PREF
28     C              IS DRAWN ON THE PRESSURE PLOT
29
30     C      COMMON/EXPDAT/NEXP,XEXP(50),PEXP(50),PREF
31
32     C      "SWITCH" VARIABLES
33
34     C      SWEND  - END OF DATA SWITCH
35     C              0 - DATA ENCOUNTERED, PROCESS IT
36     C              1 - END OF DATA ENCOUNTERED, STOP
37
38     C      SWPD   - PRINTED OUTPUT SWITCH
39     C              0 - DO NOT PRINT OUTPUT
40     C              1 - PRINT OUTPUT (DEFAULT)
41
42     C      SWGO   - GRAPHIC OUTPUT SWITCH
43     C              0 - DO NOT PLOT OUTPUT
44     C              1 - PLOT OUTPUT (DEFAULT)
45
46     C      COMMON/SWITCH/SWEND,SWPD,SWGO
47     C      INTEGER SWEND,SWPD,SWGO
48
49     C      "ARECOM" VARIABLES
50
51     C      NA     - NUMBER OF X POSITIONS DEFINING NOZZLE GEOMETRY
52
53     C      XA     - NOZZLE X COORDINATES
54
55     C      ACOEF  - SPLINE COEFFICIENTS DEFINING AREA VS X
56
57     C      COMMON/ARECOM/NA,XA,ACOEF
58
59     C      "FEED" VARIABLES
60
61     C      HFUEL  - ENTHALPY OF THE FUEL AT THE FEED
62     C              TEMPERATURE, CAL/MOL
63
64     C      TFEED  - TEMPERATURE OF THE FEED, K
65
66     C      NATOM  - NUMBER OF ATOMS OF CARBON IN A MOLECULE
67     C              OF FUEL
68
69     C      COMMON/FEED/HFUEL,TFEED,NATOM
70
71     C      "PLTBLK" VARIABLES
72
73     C      PLTBLK CONTAINS THE MINIMUM AND MAXIMUM VALUES
74     C      FOR ALL PLOT OUTPUT. IF ANY PARAMETERS ARE NOT
75     C      SPECIFIED, THE CORRESPONDING PLOT IS SCALED
76     C      AUTOMATICALLY
77
78     C      XMIN
79
80
81
82

```

```

83      C      XMAX  - DISTANCE ALONG THE NOZZLE
84      C
85      C      PMIN
86      C      PMAX  - NORMALIZED PRESSURE
87      C
88      C      TMIN
89      C      TMAX  - NORMALIZED TEMPERATURE
90      C
91      C      YMIN
92      C      YMAX  - MASS FRACTION OF LIQUID WATER
93      C
94      C      DTMIN
95      C      DTMAX  - TEMPERATURE DIFFERENCE
96      C
97      C      DNMIN
98      C      DNMAX  - NUCLEATION RATE
99      C
100     C      RMIN
101     C      RMAX  - DROPLET RADIUS
102     C
103     C      PRMIN
104     C      PRMAX  - PRESSURE RATIO
105     C
106     C      TLMIN
107     C      TLMAX  - TEMPERATURE OF LIQUID
108     C
109     C      RHOMIN
110     C      RHOMAX  - DENSITY
111     C
112     C      SMIN
113     C      SMAX  - ENTROPY
114     C
115     C      UMIN
116     C      UMAX  - FLOW VELOCITY
117     C
118     C      XMMIN
119     C      XMMAX  - MACH NUMBER
120     C
121     C      IPSLCT - PLOT SELECTION INDICATOR. IF THE VALUE IS
122     C                ZERO FOR A GIVEN INDEX, THE PLOT IS NOT
123     C                GENERATED. IF THE VALUE IS ONE FOR A GIVEN
124     C                INDEX, THE PLOT IS GENERATED. THE INDICES
125     C                FOR ALLOWED PLOTS ARE AS FOLLOWS:
126     C                1 - NORMALIZED PRESSURE
127     C                2 - PRESSURE RATIO
128     C                3 - NORMALIZED TEMPERATURE
129     C                4 - MASS FRACTION
130     C                5 - TEMPERATURE DIFFERENCE
131     C                6 - NUCLEATION RATE
132     C                7 - CRITICAL RADIUS
133     C                8 - DROPLET RADIUS (AND R*)
134     C                9 - TEMPERATURE OF LIQUID
135     C                10 - DENSITY
136     C                11 - ENTROPY PRODUCTION
137     C                12 - FLOW VELOCITY
138     C                13 - MACH NUMBER
139     C                14 - COMBINATION OF INDICES 1, 3, AND 12
140     C                15 - COMBINATION OF INDICES 4, 5, AND 6
141     C
142     C      COMMON/PLTBLK/XMIN,XMAX,PMIN,PMAX,TMIN,TMAX,
143     C      1 YMIN,YMAX,DTMIN,DTMAX,DNMIN,DNMAX,RMIN,RMAX,
144     C      2 PRMIN,PRMAX,TLMIN,TLMAX,RHOMIN,RHOMAX,
145     C      3 SMIN,SMAX,UMIN,UMAX,XMMIN,XMMAX,IPSLCT(15)
146     C
147     C      "CONST" VARIABLES
148     C
149     C      TC      - CRITICAL TEMPERATURE OF WATER, K
150     C
151     C      K      - BOLTZMANN CONSTANT, J/MOLECULE-K
152     C
153     C
154     C
155     C
156     C
157     C
158     C
159     C
160     C
161     C
162     C
163     C
164     C
165     C
166     C

```

```

167 C
168 C CAPR - UNIVERSAL GAS CONSTANT, J/MOL-K
169 C
170 C M1 - MOLECULAR MASS OF WATER, KG/MOLECULE
171 C
172 C W - MOLECULAR WEIGHT TABLE, KG/MOL
173 C
174 C RHOL - DENSITY OF WATER, KG/M**3
175 C
176 C RBAR - SPECIFIC GAS CONSTANT FOR WATER, R/M1, J/KG-K
177 C
178 C PI - AREA OF UNIT CIRCLE
179 C
180 C ALPHAC - THERMAL ACCOMMODATION COEFFICIENT FOR CARRIER
181 C GAS INTERACTION WITH WATER DROPLETS
182 C
183 COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
184 REAL K,M1
185 C
186 C "ADJUST" VARIABLES
187 C
188 C
189 C GAMMA1 - RATIO OF SPECIFIC HEATS
190 C
191 C QC - CONDENSATION COEFFICIENT
192 C
193 C ALPHA - CONSTANT IN EQUATION (78)
194 C
195 C BETA - LANGMUIR PARAMETER
196 C
197 C DSTAR - DIAMETER OF NOZZLE THROAT, M**3
198 C
199 C ASTAR - AREA OF NOZZLE THROAT, M**3
200 C
201 C DT2 - TEMPERATURE STEP FOR PART 2, K
202 C
203 C JMIN - BEGINNING NUCLEATION RATE FOR PART 3,
204 C DROPLETS FORMED/M**3-S
205 C
206 C DELX - STEP WIDTH FOR PART 3 CALCULATIONS, M
207 C
208 C EPS - CONVERGENCE ARRAY
209 C 1 - NEWTON ITERATION TO SOLVE EQUATION (57)
210 C 2 - NEWTON ITERATION TO SOLVE EQUATION (111)
211 C 3 - PRESSURE CONVERGENCE IN PART 1
212 C 4 - MASS FLUX CONVERGENCE IN PART 1
213 C 5 - PRESSURE CONVERGENCE IN PART 2
214 C 6 - NEWTON ITERATION FOR T(J-1) IN PART 3
215 C 7 - TEMPERATURE CONVERGENCE, EQUATION (133), IN PART 3
216 C 8 - NEWTON ITERATION FOR X AS A FUNCTION OF A
217 C
218 C IDUT - OUTPUT LEVEL
219 C 0 - STANDARD SUMMARY OUTPUT
220 C 1 - EXTENDED OUTPUT
221 C 2 - DEBUG OUTPUT
222 C
223 C DT1 - TEMPERATURE STEP FOR PART 1, K
224 C
225 C CVRAT - CONVERGENCE RATIO FOR DELS/CV, EQUATION (126)
226 C
227 C ARAT - CONVERGENCE RATIO FOR A'/A, EQUATION (131)
228 C
229 C JSTOP - MAXIMUM NUMBER OF BANDS IN PART 3
230 C DIMENSION STATEMENTS LIMIT THIS VALUE TO 400. ANY
231 C SMALLER NUMBER WILL PROVIDE A MEANS TO STOP THE
232 C CALCULATIONS SHORT OF THE END OF THE NOZZLE.
233 C
234 C JDB - DEBUG PRINT CONTROL FOR PART 3
235 C IF THIS VALUE IS DEFINED, 'EXTENSIVE' PRINTOUT
236 C IS PROVIDED FOR DEBUGGING BOTH BEFORE AND AFTER
237 C THE DBLIT ROUTINE FOR ALL BAND NUMBERS GREATER
238 C THAN OR EQUAL TO JDB
239 C
240 C CP - SPECIFIC HEAT CAPACITY OF MIXTURE, J/KG-K
241 C
242 C CP1 - SPECIFIC HEAT CAPACITY OF WATER, J/KG-K
243 C
244 COMMON/ADJUST/GAMMA1,QC,ALPHA,BETA,DSTAR,ASTAR,DT2,
245 1 JMIN,DELX,EPS(8),IDUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
246 REAL JMIN
247 C
248 C "INPT" VARIABLES
249 C
250 C

```

```

251      C      TO      - INITIAL TEMPERATURE, K
252      C
253      C      PO      - INITIAL PRESSURE, N/M**2
254      C
255      C      XLAST  - FINAL X, M (USED TO TERMINATE CALCULATIONS)
256      C
257      C      PHIL   - EQUIVALENCE RATIO
258      C
259      C      RHC    - ELEMENTAL RATIO OF HYDROGEN TO CARBON
260      C              IN MIXTURE
261      C
262      C      RNO    - ELEMENTAL RATIO OF NITROGEN TO OXYGEN
263      C              IN MIXTURE
264      C
265      C      COMMON/INPT/TO,PO,XLAST,PHIL,RHC,RNO
266      C
267      C      NAMELIST PARAMETERS
268      C
269      C
270      C      DESCRIPTIONS OF MOST NAMELIST PARAMETERS CAN BE
271      C      FOUND ELSEWHERE IN THIS SUBROUTINE. THE FOLLOWING
272      C      PARAMETERS ARE LOCAL TO THIS ROUTINE.
273      C
274      C      IPLTRD - INTEGER FLAG TO INDICATE IF AUTO-SCALING
275      C              IS TO BE USED ON THE PLOTS.
276      C              0 - USE AUTO-SCALING
277      C              1 - DO NOT USE AUTO-SCALING. THE NAMELIST
278      C                  "PLTOVR" MUST BE INCLUDED IN THE INPUT DATA.
279      C
280      C      RWA     - WALL COORDINATES FOR DEFINING TUNNEL GEOMETRY
281      C
282      C      DELSTR  - BOUNDARY LAYER DISPLACEMENT THICKNESSES FOR
283      C                  DEFINING TUNNEL GEOMETRY
284      C
285      C      NAMELIST/DATAIN/TO,PO,XLAST,SWPO,SWGQ,QC,ALPHA,BETA,
286      C      1 DSTAR,CVRAT,ARAT,DT1,IOUT,DT2,JMIN,DELX,EPS,
287      C      2 JSTOP,JOB,PHIL,RHC,RNO,IPLTRD,NA,XA,RWA,DELSTR,ALPHAC,
288      C      3 NEXP,XEXP,PEXP,PREF,IPSLCT,HFUEL,TFEED,NATOM
289      C      NAMELIST/PLTOVR/XMIN,XMAX,PMIN,PMAX,TMIN,TMAX,
290      C      1 YMIN,YMAX,DTMIN,DTMAX,DNMIN,DNMAX,RMIN,RMAX,
291      C      2 PRMIN,PRMAX,TLMIN,TLMAX,RHOMIN,RHOMAX,
292      C      3 SMIN,SMAX,UMIN,UMAX,XMMIN,XMMAX
293      C
294      C      SET CONSTANTS
295      C
296      C      DATA TC,K,CAPR,M1,M,RHOL/647.286,1.381E-23,8.314,2.99E-26,
297      C      1 0.018,0.044,0.028,0.032,0.002,0.028,0.001,0.016,0.017,
298      C      1 0.030,1.E3/
299      C      DATA DY/10*1./
300      C
301      C      SET DEFAULTS FOR ADJUSTABLE CONSTANTS
302      C
303      C      DATA ALPHAC/1./
304      C      DATA TO/0./
305      C      DATA HFUEL,TFEED,NATOM/-17895.,298.15,1/
306      C      DATA IPSLCT/15*0/
307      C      DATA NEXP/0/
308      C      DATA XEXP/92.,116.,140.,164.,188.,212.,224.,236.,248.,
309      C      1 260.,272.,284.,308.,320.,332.,344.,356.,392.,428.,
310      C      2 464.,500.,536.,616.,27*0./
311      C      DATA QC,ALPHA,BETA,DSTAR/1.0,9.0,
312      C      1 2.0,0.011284/
313      C      DATA SWEND/0/
314      C      DATA IPLTRD/0/
315      C      DATA XMIN,XMAX,PMIN,PMAX,TMIN,TMAX,YMIN,YMAX,
316      C      1 DTMIN,DTMAX,DNMIN,DNMAX,RMIN,RMAX/14*0./
317      C      DATA PRMIN,PRMAX,TLMIN,TLMAX,RHOMIN,RHOMAX,
318      C      1 UMIN,UMAX,SMIN,SMAX,XMMIN,XMMAX/12*0./
319      C      DATA CVRAT/1.E-3/
320      C      DATA ARAT/1.E-3/
321      C      DATA EPS/8*1.E-6/
322      C      DATA PHIL/0.8/
323      C      DATA RHC/4./
324      C      DATA RNO/3.7619/
325      C      DATA IOUT/1/
326      C      DATA DT1/1.0/
327      C      DATA DT2/0.2/
328      C      DATA NPASS/0/
329      C      DATA SWPO,SWGQ/1,1/
330      C      DATA JSTOP/100/
331      C      DATA JOB/1000/
332      C
333      C      1 FORMAT(1H1,20X,22HCONDENSATION EVOLUTION//)
334      C

```

```

335      C      SET COMPUTED CONSTANTS
336      C
337      RBAR = CAPR/W(1)
338      PI = ACOS(-1.)
339      READ(5,DATAIN,END=10)
340      10 IF(EDF(5).NE.0) GO TO 30
341      WRITE(33) TO,PO
342      IF(IPLTRD.NE.0) READ(5,PLTOVR,END=20)
343      20 IF(EDF(5).EQ.0) GO TO 40
344      30 SWEND = 1
345      40 CONTINUE
346      IF(TO.NE.0.) GO TO 50
347      TO = 1500.
348      CALL FTEMP(TFLAME)
349      NTENS = (TFLAME - 95.)/10.
350      TO = 10.*FLOAT(NTENS)
351      50 CONTINUE
352      IF(NPASS.EQ.0) WRITE(6,1)
353      IF(NPASS.EQ.0) WRITE(6,DATAIN)
354      NPASS = NPASS + 1
355      IERR = 0
356      NPM = 10
357      S = 0.0001
358      IPT = -1
359      DO 60 I=1,NA
360      Y(I) = RWA(I) - DELSTR(I)
361      60 CONTINUE
362      CALL CSOS(NPM,NA,XA,Y,DY,S,IPT,ACDEF,WK,IERR)
363      RETURN
364      END

```

```

1      SUBROUTINE DBLIT
2
3      C
4      C      SUBROUTINE DBLIT DETERMINES THE TEMPERATURE FOR WHICH
5      C      TWO INDEPENDENT CALCULATIONS OF ENTROPY ARE EQUAL AND
6      C      THE DENSITY FOR WHICH THE MASS FLOW AND CROSS
7      C      SECTIONAL AREA ARE CONSISTENT
8
9      COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
10     COMMON I,J,A(400),X(400),DELN(400),CAPJX(400),R(400),
11     1 MU(400),TL(400),T(400),P(400),RSTAR(400),
12     2 U(400),S(400),SL(400),HL(400),RHO(400),CAPJY(400),
13     3 F(400),G(400),YS(400),DELY(400),DELS(400),
14     4 RPERM(400),TS(400),OUTMCH(400),CAPPJ(400)
15     REAL MU
16     COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
17     REAL K,M1
18     COMMON/ADJUST/GAMMA1,QC,ALPHA,BETA,DSTAR,ASTAR,DT2,
19     1 JMIN,DELX,EPS(8),IOUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
20     REAL JMIN
21     COMMON/OUT1/SO,HO,MDOT,RHOSTR,TSTAR
22     REAL MDOT
23
24     C
25     SGPP = (S(J+1) - SL(J+1))/(1. - YS(J+1))
26     10 CONTINUE
27
28     C
29     EQUATION (44)
30     CALL CS(SGP,RHO(J+1),T(J+1))
31     CALL CCP(T(J+1),CP,CP1,DUM)
32
33     C
34     EQUATION (126)
35
36     USOCV = (SGPP - SGP)/(CP - CAPR*SIG)
37     IF(ABS(DSOCV).LT.CVRAT) GO TO 20
38
39     C
40     ADJUST T, EQUATION (127), AND GO BACK
41
42     T(J+1) = T(J+1)*EXPP(DSOCV)
43     GO TO 10
44
45     C
46     TEMPERATURE ITERATION HAS CONVERGED
47
48     20 CONTINUE
49     CALL CHG(T(J+1),HGP,DUM)
50
51     C
52     CALCULATE SPECIFIC ENTHALPY USING EQUATION (128)
53
54     HP = (1. - YS(J+1))*HGP + HL(J+1)
55
56     C
57     CALCULATE FLOW VELOCITY USING EQUATION (129)
58
59     U(J+1) = SQRT(2.*(HO - HP))
60
61     C
62     CALCULATE CORRESPONDING AREA USING EQUATION (130)
63
64     AP = MDOT*(1. - YS(J+1))/(RHO(J+1)*U(J+1))
65     APRAT = ABS(AP - A(J+1))/A(J+1)
66     IF(APRAT.LT.ARAT) GO TO 30
67
68     C
69     ADJUST RHO, EQUATION (132), AND GO BACK
70
71     RHO(J+1) = MDOT*(1. - YS(J+1))/(A(J+1)*U(J+1))
72     GO TO 10
73
74     C
75     DENSITY ITERATION HAS CONVERGED
76
77     30 CONTINUE
78
79     C
80     CALCULATE PRESSURE USING EQUATION (47)
81
82     P(J+1) = RHO(J+1)*CAPR*SIG*T(J+1)
83     CALL SATTEM(TS(J+1),P(J+1))
84     RETURN
85     END

```

```

1      SUBROUTINE ELEMBAL
2      REAL K1,K2,K3,K4,K5,K6
3      COMMON/RESLTS/S(11)
4      COMMON/SIGMAS/SH,SO,SN,SC
5      COMMON/CONSTS/FACTOR,EPS
6      COMMON/K1K2ETC/K1,K2,K3,K4,K5,K6
7      1 FORMAT(' *** ELEMBAL EXCEEDS 50 ITERATIONS ***')
8      S(2)=SC*FACTOR
9      S(1)=SH/2.0
10     S(4)=(SO-SC-S(1)-S(2))/2.0
11     S(6)=SN/2.0
12     S(11)=(SH+SO+SN+SC-S(1)-S(2))/2.0
13     NITER=0
14     10 CONTINUE
15     YOLD=S(2)
16     ZOLD = S(4)
17     NITER=NITER+1
18     IF(NITER.LT.51) GO TO 20
19     WRITE(6,1)
20     STOP
21
22     C      COMPUTE THE REST OF THE VARIABLES.....
23     C
24     20 CONTINUE
25     S(3)=S(2)*SQRT(K2*S(11)/S(4))
26     S(5)=S(1)*S(3)/(S(2)*K1)
27     S(10) = SQRT(K6*S(4)*S(6))
28     S(6) = (SN-S(10))/2.0
29     S(9)=SQRT(K3*S(4)*S(5))
30     S(7)=SQRT(K4*S(5)*S(11))
31     S(8)=SQRT(K5*S(4)*S(11))
32     S(1)=(SH-2.0*S(5)-S(7)-S(9))/2.0
33     S(2)=SC-S(3)
34     S(4)=(S(4)+(SO-SC-S(1)-S(2)-S(8)-S(9)-S(10))/2.0) /2.0
35     S(11)=S(1)+S(2)+S(3)+S(4)+S(5)+S(6)+S(7)+S(8)+S(9)+S(10)
36
37     C      CHECK FOR CONVERGENCE.....
38     C
39     DY=YOLD-S(2)
40     DZ = ZOLD - S(4)
41     IF(NITER .EQ. 1) GO TO 10
42     IF (ABS(DY/S(2)) .LE. EPS) GO TO 30
43     GO TO 10
44     30 CONTINUE
45     IF(ABS(DZ)/S(4).LE.EPS) GO TO 40
46     GO TO 10
47     40 CONTINUE
48     S(3)=S(2)*SQRT(K2*S(11)/S(4))
49     S(5)=S(1)*S(3)/(S(2)*K1)
50     S(10) = SQRT(K6*S(4)*S(6))
51     S(6) = (SN-S(10))/2.0
52     S(9)=SQRT(K3*S(4)*S(5))
53     S(7)=SQRT(K4*S(5)*S(11))
54     S(8)=SQRT(K5*S(4)*S(11))
55     RETURN
56     END

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

1      FUNCTION EXPP(VAL)
2
3      C      FUNCTION EXPP IS A UTILITY USED TO AVOID THE UNDERFLOW
4      C      MESSAGE ASSOCIATED WITH VERY SMALL ARGUMENTS
5      C
6      EXPP = 0.
7      IF(VAL.LT.-670.) GO TO 10
8      EXPP = EXP(VAL)
9      10 CONTINUE
10     RETURN
11     END

```

```

1      SUBROUTINE FITLAM(LAMBDA,T)
2
3      C      SUBROUTINE FITLAM DETERMINES THE THERMAL CONDUCTIVITY
4      C      OF EACH SPECIES AS A POLYNOMIAL IN TERMS OF TEMPERATURE
5      C
6      DIMENSION LAMBDA(10)
7      REAL LAMBDA
8      DIMENSION COEF(4,10)
9
10     C      COEFFICIENTS IN EXPRESSION FOR THERMAL
11     C      CONDUCTIVITY E(N,K) ... TABLE B4
12     C
13     DATA COEF/-0.2045,1.7566E-3,-4.6279E-6,4.2102E-9,
14     1 -1.4403E-5,2.5166E-5,1.3405E-7,-1.1069E-10,
15     2 5.3712E-4,8.8425E-5,-1.5431E-8,-1.8246E-11,
16     3 -3.8505E-3,1.3168E-4,-1.2385E-7,8.1162E-11,
17     4 -5.5274E-2,1.2443E-3,-1.9310E-6,1.3762E-9,
18     5 -3.0706E-3,1.3215E-4,-1.4900E-7,1.0324E-10,
19     6 12*0.,-1.8772E-3,1.1087E-4,-6.9710E-8,2.7900E-11/
20
21     C      EQUATION (66)
22     C
23     DO 20 I=1,10
24     LAMBDA(I) = 0.
25     DO 10 J=1,4
26     LAMBDA(I) = LAMBDA(I) + COEF(J,I)*T**(J-1)
27     10 CONTINUE
28     20 CONTINUE
29     RETURN
30     END

```

```

1      SUBROUTINE FITMU(MU,T)
2
3      C      SUBROUTINE FITMU DETERMINES THE VISCOSITY OF EACH
4      C      SPECIES AS A POLYNOMIAL IN TERMS OF TEMPERATURE
5      C
6      DIMENSION MU(10)
7      REAL MU
8      DIMENSION COEF(4,10)
9
10     C      COEFFICIENTS IN EXPRESSION FOR VISCOSITY
11     C      D(N,K) ... TABLE B3
12     C
13     DATA COEF/-1.5371E-5,1.5429E-7,-3.1981E-10,2.7958E-13,
14     1 -2.5212E-7,5.5024E-8,-1.2381E-11,-5.5279E-15,
15     2 -4.9877E-7,7.8689E-8,-6.9794E-11,3.6438E-14,
16     3 -5.7709E-7,8.8852E-8,-7.0382E-11,3.4305E-14,
17     4 1.6225E-6,2.9338E-8,-1.9878E-11,1.1391E-14,
18     5 -6.0917E-8,7.6311E-8,-6.4962E-11,3.2374E-14,
19     6 12*0.,-8.4886E-7,8.5390E-8,-7.1595E-11,3.5702E-14/
20
21     C      EQUATION (63)
22     C
23     DO 20 I=1,10
24     MU(I) = 0.
25     DO 10 J=1,4
26     MU(I) = MU(I) + COEF(J,I)*T**(J-1)
27     10 CONTINUE
28     20 CONTINUE
29     RETURN
30     END

```



```

1      SUBROUTINE FTEMP(TFLAME)
2
3      C
4      C      SUBROUTINE FTEMP COMPUTES THE FLAME TEMPERATURE OF
5      C      HYDROCARBON COMBUSTION IN AIR WITH OR WITHOUT
6      C      OXYGEN ENRICHMENT.....
7      C      CONSTANT PRESSURE FORMULATION....
8      C      REFERENCE TEMPERATURE IS 298.15 KELVIN
9
10     COMMON/INPT/TO,PO,XLAST,PHI1,RHC,RNO
11     COMMON/TANDP/TXX,PXX
12     COMMON/RESLTS/S(11)
13     COMMON/FEED/HFUEL,TFEED,NATOM
14     COMMON/COEFCU/COEF(10,8,2)
15
16     C
17     1 FORMAT(/,2X,'DID NOT CONVERGE IN 20 ITERATIONS')
18     2 FORMAT(/,2X,'ENTHALPY OF THE FEED (CAL/KG.) = ',F12.4)
19     3 FORMAT(/,2X,'FLAME TEMPERATURE (KELVIN) = ',F8.2)
20     4 FORMAT(/,2X,'DENSITY OF THE MIXTURE(KG/CU.M)=',E12.6)
21     5 FORMAT(/,2X,'ENTHALPY OF THE MIXTURE (CAL/KG.) = ', F12.4)
22     VAL(I,J,T) = (COEF(I,1,J)*ALOG(T) + COEF(I,2,J)*T
23     1 + COEF(I,3,J)*T**2/2. + COEF(I,4,J)*T**3/3.
24     2 + COEF(I,5,J)*T**4/4. + COEF(I,6,J)*T**5/5. + COEF(I,7,J))
25
26     C
27     C      HFUEL = ENTHALPY OF THE FUEL AT THE FEED TEMPERATURE (CAL/MOL)
28     C      TFEED = TEMPERATURE OF THE FEED (KELVIN)
29     C      N = NUMBER OF ATOMS OF CARBON IN A MOLECULE OF FUEL.
30     C      TFO = FIRST GUESS OF FLAME TEMPERATURE, KELVIN.
31     C      PO = PRESSURE OF THE FEED (BARS)
32
33     C      COMPUTE SIGMA(H), SIGMA(O), SIGMA(N), AND SIGMA(C)
34     C      IN 1 KG OF THE MIXTURE.....
35
36     C      EQUATION (8)
37     SO=500.0/( 8.0+7.0*RNO+PHI1*(12.0+RHC)/(4.0+RHC) )
38
39     C      EQUATION (9)
40     SC = 2.0*PHI1*SO/(4.0 + RHC)
41
42     C      EQUATION (11)
43     SH=RHC*SC
44
45     C      EQUATION (10)
46     SN=SO*RNO
47
48     C      ENTHALPY OF THE FEED....
49     C      FUEL HAS THE FORMULA CNHM
50     C      THERE ARE N MOLS OF CARBON IN ONE MOL OF THE FUEL.
51
52     C      HFEED=HFUEL * SC * FLOAT(NATOM)
53     C      HFEED=HFEED+VAL(4,1,TFEED)*SO/2.0+VAL(6,1,TFEED)*SN/2.0
54
55     C      COMPUTE THE EQUILIBRIUM COMPOSITION AT TFO AND PO.....
56     C      COMPUTE THE ENTHALPY.....
57
58     C      TXX = TO
59     C      PXX = PO
60     C      CALL CECOMP
61     C      TFO = TXX
62     C      CALL CHG(TFO,H0,DUMMY)
63
64     C
65     C      NOTE: SUBR CHG RETURNS H IN JOULES/KG.
66
67     C
68     T1=TFO-100.0
69     DH1=HFEED-H0/4.184
70     DO 10 ITER=1,20
71     TXX = T1
72     CALL CECOMP
73     CALL CHG(T1,H1,DUMMY)
74     DH2=HFEED-H1/4.184
75     TFLAME=(DH2*TFO-DH1*T1)/(DH2-DH1)
76     IF(ABS(TFLAME-T1) .LE. 0.001) GO TO 20
77     TFO=T1
78     T1=TFLAME
79     DH1=DH2
80 10 CONTINUE
81     WRITE(6,1)
82     STOP

```

```

83      20 CONTINUE
84      DENSITY=PO/8.314/S(11)/TFLAME
85      WRITE(6,2) HFEED
86      WRITE(6,3) TFLAME
87      WRITE(6,4) DENSITY
88      WRITE(6,5) H1
89      RETURN
90      END

```

```

1      SUBROUTINE GRL(ZZ)
2
3      C      SUBROUTINE GRL CALCULATES THE GROWTH RATE
4      C      FOR LARGE DROPLETS (I.E., Z > 1.1)
5      C
6      COMMON/EQCON/DELTAT,CAPL,NU,PSI,DRDT,
7      1 TR,LTILDA,KN,THETA,LAMBDA,PR,XI,OMEGA,CAPLAM
8      REAL NU,LTILDA,KN,LAMBDA
9      COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
10     REAL K,M1
11     COMMON/ADJUST/GAMMA1,QC,ALPHA,BETA,DSTAR,ASTAR,DTZ,
12     1 JMIN,DELX,EPS(8),IOUT,DT1,CVRAT,ARAT,JSTOP,JOB,CP,CP1
13     REAL JMIN
14     COMMON I,J,A(400),X(400),DELN(400),CAPJX(400),R(400),
15     1 MU(400),TL(400),T(400),P(400),RSTAR(400),
16     2 U(400),S(400),SL(400),HL(400),RHO(400),CAPJY(400),
17     3 F(400),G(400),YS(400),DELY(400),DELS(400),
18     4 RPERM(400),TS(400),OUTHCH(400),CAPPJ(400)
19     REAL MU
20
21     C      ZOLD = ZZ
22     RAT = R(I)/RSTAR(J)
23     CAPDEL = CAPLAM*DELTAT
24     ZPRIME = (THETA**3/(THETA + 1.))*ALOG(RAT + THETA)
25     1 + (1./(THETA + 1.) + OMEGA)*ALOG(RAT - 1.)
26     2 + (OMEGA + 1. - THETA)*RAT + 0.5*RAT**2 + CAPDEL
27     10 CONTINUE
28
29     C      EQUATION (112)
30     C
31     FZ2 = (THETA**3/(THETA + 1.))*ALOG(ZOLD + THETA)
32     1 + (1./(THETA + 1.) + OMEGA)*ALOG(ZOLD - 1.)
33     2 + (OMEGA + 1. - THETA)*ZOLD + 0.5*ZOLD**2 - ZPRIME
34
35     C      EQUATION (113)
36     C
37     FZ2P = THETA**3/((THETA + 1.)*(ZOLD + THETA))
38     1 + (1. + OMEGA*(THETA + 1.))/((THETA + 1.)*(ZOLD - 1.))
39     2 + ZOLD + OMEGA + 1. - THETA
40
41     C      EQUATION (114)
42     C
43     ZNEW = ZOLD - FZ2/FZ2P
44     IF(ABS(ZNEW - ZOLD)/ZNEW.LT.EPS(2)) GO TO 20
45     ZOLD = ZNEW
46     GO TO 10
47
48     20 CONTINUE
49     ZZ = ZNEW
50     RETURN
51     END

```

```

1      SUBROUTINE GRLPRP
2
3      C      SUBROUTINE GRLPRP CALCULATES SEVERAL VARIABLES
4      C      PREPARATORY FOR EVALUATION OF THE GROWTH RATE FOR
5      C      LARGE DROPLETS
6
7      C      COMMON/SIGCOM/SIGMA(10),SIG,PSUP0
8      C      DIMENSION WORK(10)
9      C      COMMON/EQCOM/DELTAT,CAPL,NU,PSI,DRDT,
10     C      1 TR,LTILDA,KN,THETA,LAMBDA,PR,XI,OMEGA,CAPLAM
11     C      REAL NU,LTILDA,KN,LAMBDA
12     C      COMMON/INPT/TO,PO,XLAST,PHI1,RHC,RND
13     C      COMMON/SWITCH/SWEND,SWPO,SWGO
14     C      INTEGER SWEND,SWPO,SWGO
15     C      COMMON/OUT2/U2,RHO2,CAPJ2,T2,P2,RSTAR2,X2,A2,SIG2(11),OUMC
16     C      COMMON/CMOUT3/NENT
17     C      COMMON/CUT1/SO,HQ,MDOT,RHOSTR,TSTAR
18     C      REAL MDOT
19     C      REAL KNST
20     C      COMMON/ADJUST/GAMMA1,QC,ALPHA,BETA,DSTAR,ASTAR,DT2,
21     C      1 JMIN,DELX,EPS(8),IOUT,DT1,CYRAT,ARAT,JSTOP,JDB,CP,CP1
22     C      REAL JMIN
23     C      COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
24     C      REAL K,M1
25     C      COMMON I,J,A(400),X(400),DELN(400),CAPJX(400),R(400),
26     C      1 MU(400),TL(400),T(400),P(400),RSTAR(400),
27     C      2 U(400),S(400),SL(400),HL(400),RHO(400),CAPJY(400),
28     C      3 F(400),G(400),YS(400),DELY(400),DELS(400),
29     C      4 RPERM(400),TS(400),OUTHCH(400),CAPPJ(400)
30     C      REAL MU
31     C      REAL MUU
32
33     C      CALL SATTEM(TSP,P(J))
34     C      CALL CHG(T(J),HGX,HG1)
35
36     C      EQUATION (56)
37
38     C      CAPL = HG1 - 4.2E+3*T(J) + 17.11753658E+6
39     C      CALL CCP(T(J),CP,CP1,CPC)
40     C      WAVG = 0.
41     C      WC = 0.
42     C      DO 10 IJ=1,10
43     C      WAVG = WAVG + W(IJ)*SIGMA(IJ)
44     C      IF(IJ.NE.1) WC = WC + W(IJ)*SIGMA(IJ)
45     C      10 CONTINUE
46     C      WAVG = WAVG/SIG
47     C      WC = WC/(SIG - SIGMA(1))
48     C      WRAT = W(1)/WAVG
49     C      Y1 = SIGMA(1)/SIG
50
51     C      EQUATION (39)
52
53     C      GAMMA1 = CP1/(CP1 - CAPR/W(1))
54
55     C      EQUATION (41)
56
57     C      GAMMAC = CPC/(CPC - CAPR/WC)
58
59     C      EQUATION (74)
60
61     C      FF = Y1*SQRT(WRAT) + (1. - Y1)*SQRT(WC/WAVG)*(GAMMA1/GAMMAC)
62     C      1 *((GAMMAC + 1.)/(GAMMA1 + 1.))*(CPC/CP1)*ALPHAC
63
64     C      EQUATION (78)
65
66     C      NU = ((CAPR/W(1))*TSP/CAPL)*(ALPHA + 0.5 - ((2. - QC)/(2.*QC))
67     C      1 *((GAMMA1 + 1.)/(2.*GAMMA1))*((CP1*TSP)/CAPL)
68     C      2 *(FF/Y1)/SQRT(WRAT))
69     C      TR = T(J)/TC
70     C      CALL FITMU(WORK,T(J))
71     C      CALL MIXMU(MUU,WORK)
72
73     C      EQUATION (68)
74
75     C      LTILDA = 1.5*MUU*SQRT(CAPR*SIG*T(J))/P(J)
76
77     C      EQUATION (71)
78
79     C      KNST = LTILDA/(2.*RSTAR(J))
80
81     C      EQUATION (75)
82

```

```

83      THETA = 2.*BETA*KNST
84      CALL FITLAM(WORK,T(J))
85      CALL MIXLAM(LAMBDA,WORK)
86      C
87      C      EQUATION (69)
88      C
89      PR = CP1*MUU/LAMBDA
90      C
91      C      EQUATION (77)
92      C
93      XI = SQRT(8.*PI)*(2.*GAMMA1)/(1.5*(GAMMA1 + 1.))
94      C
95      C      EQUATION (73)
96      C
97      OMEGA = XI*(1. - NU)*KNST/(PR*FF)
98      C
99      C      EQUATION (76)
100     C
101     CAPLAM = LAMBDA*(TSP-T(J))/(CAPL*RHOL*RSTAR(J)**2)
102     RETURN
103     END

1      FUNCTION GRS(ZZ)
2      C
3      C      FUNCTION GRS CALCULATES THE GROWTH RATE FOR
4      C      SMALL DROPLETS (I.E., Z < 1.1)
5      C
6      COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
7      COMMON/EQCOM/DELTAT,CAPL,NU,PSI,DRDT,
8      1 TR,LTILDA,KN,THETA,LAMBDA,PR,XI,OMEGA,CAPLAM
9      REAL NU,LTILDA,KN,LAMBDA
10     COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
11     REAL K,M1
12     COMMON/ADJUST/GAMMA1,OC,ALPHA,BETA,DSTAR,ASTAR,DTZ,
13     1 JMIN,DELX,EPS(8),IOUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
14     REAL JMIN
15     COMMON I,J,A(400),X(400),DELN(400),CAPJX(400),R(400),
16     1 MU(400),TL(400),T(400),P(400),RSTAR(400),
17     2 U(400),S(400),SL(400),HL(400),RHO(400),CAPJY(400),
18     3 F(400),G(400),YS(400),DELY(400),DELS(400),
19     4 RPERM(400),TS(400),OUTHCH(400),CAPPJ(400)
20     REAL MU
21     CALL CCP(T(J),CP,CP1,CPC)
22     WAVG = 0.
23     WC = 0.
24     DO 10 IJ=1,10
25     WAVG = WAVG + W(IJ)*SIGMA(IJ)
26     IF(IJ.NE.1) WC = WC + W(IJ)*SIGMA(IJ)
27     10 CONTINUE
28     WAVG = WAVG/SIG
29     WC = WC/(SIG - SIGMA(1))
30     WRAT = W(1)/WAVG
31     Y1 = SIGMA(1)/SIG
32     C
33     C      EQUATION (39)
34     C
35     GAMMA1 = CP1/(CP1 - CAPR/W(1))
36     C
37     C      EQUATION (41)
38     C
39     GAMMAC = CPC/(CPC - CAPR/WC)
40     C
41     C      EQUATION (74)
42     C
43     FF = Y1*SQRT(WRAT) + (1. - Y1)*SQRT(WC/WAVG)*(GAMMA1/GAMMAC)
44     1 *((GAMMAC + 1.)/(GAMMA1 + 1.))*(CPC/CP1)*ALPHAC
45     C
46     C      EQUATION (80)
47     C
48     PSI = FF*P(J)/SQRT(2.*PI*CAPR*SIG*T(J))*((GAMMA1 + 1.)/(2.*GAMMA1))
49     1 *CP1*RSTAR(J)/(CAPL*RHOL*(1. - NU))*(TS(J) - T(J))
50     PSIBAR = PSI/(R(I)*RSTAR(J))
51     DRDT = (RSTAR(J+1) - RSTAR(J))/DELTAT
52     C
53     C      EQUATION (79)
54     C
55     SOL = 1. + RSTAR(J)/RSTAR(J+1)*(ZZ - 1.)*EXPP(PSIBAR*DELTAT)
56     1 - (1./((PSIBAR*RSTAR(J+1))*DRDT*(EXPP(PSIBAR*DELTAT) - 1.))
57     GRS = SOL
58     RETURN
59     END

```

```

1      REAL FUNCTION KPJ(B,T)
2      DIMENSION B(6)
3
4      C
5      C
6      C      EVALUATE EQUATION (35) FOR THE EQUILIBRIUM CONSTANTS
7
8      KPJ = EXPP(B(1)/T + B(2) + B(3)*T + B(4)*T**2
9      1 + B(5)*T**3 + B(6)*T**4)
10     RETURN
11     END

```

```

1      SUBROUTINE MIXLAM(LAMBDA,LAMBDAL)
2
3      C
4      C      SUBROUTINE MIXLAM CALCULATES THE THERMAL CONDUCTIVITY
5      C      OF THE MIXTURE
6
7      DIMENSION LAMBDAL(6)
8      REAL LAMBDA,LAMBDAL
9      COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
10
11     C
12     C      EQUATION (67)
13
14     SUM = 0.
15     DO 10 I=1,10
16     IF(LAMBDAL(I).EQ.0.) GO TO 10
17     SUM = SUM + SIGMA(I)/LAMBDAL(I)
18 10 CONTINUE
19     LAMBDA = SIG/SUM
20     SUM = 0.
21     DO 20 I=1,10
22     SUM = SUM + SIGMA(I)*LAMBDAL(I)
23 20 CONTINUE
24     LAMBDA = 0.5*(SUM/SIG + LAMBDA)
25     RETURN
26     END

```

```

1      SUBROUTINE MIXMU(MU,MUI)
2
3      C
4      C      SUBROUTINE MIXMU CALCULATES THE VISCOSITY OF THE
5      C      GASEOUS MIXTURE
6
7      COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
8      REAL K,M1
9      DIMENSION MUI(10)
10     REAL MU,MUI
11     COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
12
13     C
14     C      EQUATION (64)
15
16     MU = 0.
17     DO 20 I=1,10
18     SUM = 0.
19     DO 10 J=1,10
20     IF(J.EQ.I) GO TO 10
21     IF(MUI(J).EQ.0.) GO TO 10
22     PHI = (1. + SQRT(MUI(I)/MUI(J))*(W(J)/W(I))**0.25)**2
23     PHI = PHI/(SQRT(8.)*SQRT(1. + W(I)/W(J)))
24     SUM = SUM + SIGMA(J)*PHI
25 10 CONTINUE
26     IF(SIGMA(I).EQ.0.) GO TO 20
27     MU = MU + MUI(I)/(1. + SUM/SIGMA(I))
28 20 CONTINUE
29     RETURN
30     END

```

```

1      SUBROUTINE NUCRAT(CAPJ,T,P)
2
3      C
4      C      SUBROUTINE NUCRAT CALCULATES THE NUCLEATION RATE, J
5      C
6      COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
7      COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
8      REAL K,M1
9      COMMON/ADJUST/GAMMA1,OC,ALPHA,BETA,DSTAR,ASTAR,DT2,
10     1 JMIN,DELX,EPS(8),IDUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
11     REAL JMIN
12
13     C
14     C      EQUATION (57)
15     C
16     PINF = EXPP(55.897 - 6641.7/T - 4.4864*ALOG(T))
17     PBAR = (P/PINF)*(SIGMA(1)/SIG)
18     TR = T/TC
19
20     C
21     C      EQUATION (58)
22     C
23     SIGMAX = (82.27 + 75.612*TR - 256.889*TR**2 + 95.928*TR**3)
24     1 *1.E-3
25
26     C
27     C      EQUATION (59)
28     C
29     RSTARX = 2.*SIGMAX/(RHOL*RBAR*T*ALOG(PBAR))
30     CALL CHG(T,HGX,HG1)
31
32     C
33     C      EQUATION (56)
34     C
35     CAPL = HG1 - 4.2E+3*T + 17.11753658E+6
36     RHOX = P/(CAPR*SIG*T)
37     GAMMA1 = CP1/(CP1 - CAPR/W(1))
38
39     C
40     C      EQUATION (62)
41     C
42     O = 2.*(GAMMA1 - 1.)*CAPL*(CAPL/(RBAR*T) - 0.5)/(RBAR*T
43     1 *(GAMMA1 + 1.))
44     WAVG = 0.
45     DO 10 I=1,10
46     WAVG = WAVG + SIGMA(I)*W(I)
47     10 CONTINUE
48     WAVG = WAVG/SIG
49     WRAT = (W(1)/WAVG)**2
50
51     C
52     C      EQUATION (61)
53     C
54     CAPJ = (1./(1. + O))*OC*WRAT*SQRT(2.*SIGMAX/(PI*M1**3))
55     1 *(RHOX**2/RHOL)*EXPP(-4.*PI*SIGMAX*RSTARX**2/(3.*K*T))
56     CAPJ = CAPJ*(SIGMA(1)/SIG)**2
57     RETURN
58     END

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

1      SUBROUTINE PART1
2
3      C      STAGNATION CONDITIONS AND MASS FLOW RATE
4      C
5      COMMON/CONST/TC,K,CAPR,M1,W(10),KHOL,RBAR,PI,ALPHAC
6      REAL K,M1
7      COMMON/GAMOUT/GAMBAR
8      COMMON/ADJUST/GAMMA1,OC,ALPHA,BETA,DSTAR,ASTAR,DT2,
9      1 JMIN,DELX,EPS(8),IOUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
10     REAL JMIN
11     COMMON/SWITCH/SWEND,SWPO,SWGO
12     INTEGER SWEND,SWPO,SWGO
13     COMMON/INPT/TO,PO,XLAST,PHI1,RHC,RNO
14     COMMON/TANDP/TXX,PXX
15     COMMON/CUT1/SO,H0,MDOOT,RHODSTR,TSTAR
16     REAL MDOOT
17     COMMON/CMOUT1/NENTRY,DT,RHOO,T1,H1,U1,USTAR,URHO,RHOF1
18     COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
19
20     C      COMPUTE ASTAR, AREA AT NOZZLE THROAT
21     C
22     NENTRY = 0
23     ASTAR = PI/4.*DSTAR**2
24
25     C      COMPUTE H0 = HG USING EQUATION (42) WITH T = TO
26     C
27     TXX = TO
28     PXX = PO
29     CALL CECOMP
30     CALL CHG(TO,H0,DUM1)
31     RHOO = PO/(CAPR*SIG*T0)
32
33     C      COMPUTE SO = SG USING EQUATION (44) WITH T = TO, RHO = RHOO
34     C
35     CALL CS(SO,RHOO,T0)
36
37     C      MAKE INITIAL GUESS FOR T
38     C
39     T1 = 0.9*T0
40     TXX = T1
41     PXX = PO
42     DT = DT1
43     URHOX = 0.
44     10 CONTINUE
45     NENTRY = NENTRY + 1
46     20 CONTINUE
47     CALL CECOMP
48
49     C      COMPUTE DENSITY USING EQUATION (45)
50     C
51     CALL COEN(RHOF1,S0,T1)
52
53     C      COMPUTE PRESSURE USING EQUATION (47)
54     C
55     P = RHOF1*CAPR*SIG*T1
56     DIF = ABS(PXX - P)
57
58     C      TEST FOR CONVERGENCE ON PRESSURE
59     C
60     IF(DIF/P.LT.EPS(3)) GO TO 30
61     PXX = P
62     GO TO 20
63     30 CONTINUE
64     CALL CHG(T1,HGF,DUM1)
65
66     C      COMPUTE FLOW VELOCITY USING EQUATION (103)
67     C
68     UF = SQRT(2.*(H0 - HGF))
69     H1 = HGF
70     U1 = UF
71
72     C      COMPUTE MASS FLUX
73     C
74     URHO = RHOF1*UF
75     GAMBAR = ALOG(T1/TO)/ALOG(P/PO)
76     GAMBAR = 1./(1. - GAMBAR)
77     IF(IOUT.GT.1.AND.SWPO.EQ.1) CALL PRTOUT(1,2)
78
79     C      IF PAST A MAXIMUM FOR MASS FLUX BRANCH TO CHANGE
80     C      RESOLUTION TO LOCATE THE MAXIMUM
81     C
82     IF(URHO.LT.URHOX) GO TO 40

```

```

83      URHOX = URHO
84      T1 = T1 - DT1
85      TXX = T1
86      GO TO 10
87  C
88  C      PAST A MAXIMUM, RESTORE LAST T AND DECREASE
89  C      DELTA T - GO BACK AND TRY AGAIN
90  C
91      40 TST = ABS(URHO - URHOX)/URHO
92      IF(TST.LT.EPS(4)) GO TO 50
93      T1 = T1 + 2.0*DT1
94      TXX = T1
95      DT1 = 0.5*DT1
96      URHOX = 0.
97      GO TO 10
98  C
99  C      HAVE FOUND A MAXIMUM MASS FLUX
100  C      SET TSTAR = T, RHOSTR = RHO, USTAR = U
101  C
102      50 TSTAR = T1
103      RHOSTR = RHOF1
104      USTAR = UF
105  C
106  C      COMPUTE MASS FLOW RATE, MDOT USING EQUATION (104)
107  C
108      MDOT = RHOF1*UF*ASTAR
109      IF(SWPO.EQ.1) CALL PRTOU(1,0)
110      RETURN
111      END

```



```

1      SUBROUTINE PART2
2
3      C      ISENTROPIC EXPANSION FROM NOZZLE THROAT
4      C
5      COMMON/SIGCOM/SIGMA(10),SIG,PSUP0
6      COMMON/SVX2/X22,Y22
7      COMMON/GAMOUT/GAMBAR
8      COMMON/SWITCH/SWEND,SWPD,SWG0
9      COMMON/PLTOUT/NOUT,TOUT(600),POUT(600),XOUT(600),
10     1 DELTT(600),UOUT(600),OUTHAC(600)
11     INTEGER SWEND,SWPD,SWG0
12     COMMON/INPT/TO,PO,XLAST,PHI1,RHC,RNO
13     COMMON/TANDP/TXX,PXX
14     COMMON/OUT1/SO,H0,MDOOT,RHOSTR,TSTAR
15     REAL MDOOT
16     COMMON/CMOUT1/NENTRY,DT,RH00,T1,H1,U1,USTAR,URHO,RHOF1
17     COMMON/ADJUST/GAMMA1,OC,ALPHA,BETA,DSTAR,ASTAR,DT2,
18     1 JMIN,DELX,EPS(8),IOUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
19     REAL JMIN
20     COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
21     REAL K,M1
22     COMMON/OUT2/U2,RH02,CAPJ2,T2,P2,RSTAR2,X2,A2,SIG2(11),QUMC
23     COMMON/CMOUT2/NE,T2W,SIGMAX,U2W,RHO,P,PINF,PBAR,TR,H2W,RSTAR,CAPL,
24     1 Q,J
25     REAL J
26
27     C
28     1 FORMAT(1H0,'***** ARRAY SIZE EXCEEDED IN PART 2 *****')
29     2 FORMAT(1H0,'***** END OF NOZZLE ENCOUNTERED WITH INSUFFICIENT'
30     1 , ' VALUE OF J *****')
31
32     C      START WITH T = TSTAR AND RHO = RHOSTR
33     C
34     NENTRY = 0
35     NENTRY2 = 0
36     IBR = 0
37     XOLD = 0.
38     T2W = TSTAR
39
40     C      DECREASE T BY DT2
41     C
42     NE = 0
43     P = RHOSTR*CAPR*SIG*TSTAR
44     10 CONTINUE
45     NE = NE + 1
46     T2W = T2W - DT2
47     TXX = T2W
48     20 CONTINUE
49     PXX = P
50     CALL CECOMP
51
52     C      CALCULATE DENSITY USING EQUATION (45)
53     C
54     CALL CDEN(RHOZZ,S0,T2W)
55
56     C      CALCULATE PRESURE USING EQUATION (47)
57     C
58     PZZ = RHOZZ*CAPR*SIG*T2W
59     DIF = ABS(P - PZZ)
60     IF(DIF/PZZ.LT.EPS(5)) GO TO 30
61     P = PZZ
62     GO TO 20
63     30 CONTINUE
64
65     C      CONVERGENCE IN PRESSURE ITERATION
66     C      CALCULATE ENTHALPY USING EQUATION (42)
67     C
68     CALL CHG(T2W,HG,DUM)
69
70     C      CALCULATE FLOW VELOCITY USING EQUATION (103)
71     C
72     U2W = SQRT(2.*(H0 - HG))
73     H2W = HG
74     RHO = RHOZZ
75     NOUT = NE
76     TOUT(NOOUT) = T2W/TO
77     POUT(NOOUT) = P/PO
78     UOUT(NOOUT) = U2W
79     CALL SATTEMITS,P)
80     DELTT(NOOUT) = TS - T2W
81     IF(DELTT(NOOUT).LT.0.) DELTT(NOOUT) = 0.
82
83     C      CALCULATE CP1 USING EQUATION (38)

```

```

83      C      CALL CCP(T2W,CP,CP1,CPC)
84
85      C
86      C      CALCULATE GAMMA1 USING EQUATION (39)
87      C
88      GAMMA1 = CP1/(CP1 - CAPR/W(1))
89      OUTMAC(NOUT) = GAMMA1*CAPR*SIG*T2W
90      OUTMAC(NOUT) = U2W/SQRT(OUTMAC(NOUT))
91
92      C      CALCULATE PINF USING EQUATION (57)
93      C
94      PINF = EXPP(55.897 - 6641.7/T2W - 4.4864*ALOG(T2W))
95      PBAR = (P/PINF)*(SIGMA(1)/SIG)
96
97      C      CALCULATE AREA USING EQUATION (105)
98      C
99      ALST = MDOT/(RHO*U2W)
100
101      C      GET X POSITION CORRESPONDING TO THIS AREA
102      C
103      CALL XYSA(ALST,XLST)
104      IF((XLST - XOLD).GT.0.1) DT2 = 0.5*DT2
105      XOLD = XLST
106      IF(NOUT.GT.595) WRITE(6,1)
107      IF(NOUT.GT.595) STOP 'TOO MANY POINTS'
108      XOUT(NOUT) = XLST
109      X2 = XLST
110      GAMBAR = ALOG(T2W/T0)/ALOG(P/P0)
111      GAMBAR = 1./(1. - GAMBAR)
112      NENTRY = NENTRY + 1
113      IF(PBAR.GE.1..AND.NENTRY2.EQ.0) NENTRY = 1
114      IF(IOUT.GT.1..AND.SWPO.EQ.1) CALL PRTOUT(2,1)
115      IF(PBAR.GE.1..AND.NENTRY2.EQ.0) NENTRY = NENTRY + 1
116      IF(IBR.EQ.0..AND.X2.GT.XLAST) WRITE(6,2)
117      IF(IBR.EQ.0..AND.X2.GT.XLAST) STOP 'END OF NOZZLE'
118
119      C      BRANCH BACK FOR S.LT.1
120      C
121      IF(PBAR.LT.1.) GO TO 10
122      IF(NENTRY2.EQ.0) X22 = XLST
123      IF(NENTRY2.EQ.0) Y22 = POUT(NOUT)
124      NENTRY2 = NENTRY2 + 1
125      TR = T2W/TC
126
127      C      CALCULATE SIGMAX FROM EQUATION (58)
128      C
129      SIGMAX = (82.27 + 75.612*TR - 256.889*TR**2 + 95.928*TR**3)
130      1 *1.E-3
131
132      C      CALCULATE HG1 USING EQUATION (43)
133      C
134      CALL CHG(T2W,DUM,HG1)
135
136      C      CALCULATE LATENT HEAT OF EVAPORATION
137      C      USING EQUATION (56)
138      C
139      CAPL = HG1 - 4.2E+3*T2W + 17.11753658E+6
140
141      C      CALCULATE CRITICAL DROPLET RADIUS USING EQUATION (59)
142      C
143      RSTAR = 2.*SIGMAX/(RHOL*RBAR*T2W*ALOG(PBAR))
144      CALL CCP(T2W,CP,CP1,CPC)
145      GAMMA1 = CP1/(CP1 - CAPR/W(1))
146      WAVG = 0.
147      DO 40 I=1,10
148      WAVG = WAVG + SIGMA(I)*W(I)
149      40 CONTINUE
150      WAVG = WAVG/SIG
151      WRAT = (W(1)/WAVG)**2
152
153      C      CALCULATE Q USING EQUATION (62)
154      C
155      Q = 2.*(GAMMA1 - 1.)*CAPL*(CAPL/(RBAR*T2W) - 0.5)/(RBAR*T2W
156      1 *(GAMMA1 + 1.))
157
158      C      CALCULATE NUCLEATION RATE USING EQUATION (61)
159      C
160      J = (1./(1. + Q))*QC*WRAT*SQRT(2.*SIGMAX/(PI*M1**3))*(RHO**2
161      1 /RHOL)*EXPP(-4.*PI*SIGMAX*RSTAR**2/(3.*K*T2W))
162      J = J*(SIGMA(1)/SIG)**2
163      IF(IOUT.GT.1..AND.SWPO.EQ.1) CALL PRTOUT(2,2)
164
165      C      BRANCH BACK IF J.LT.JMIN
166      C

```

ORIGINAL PAGE IS
OF POOR QUALITY

```
167      IF(IJ.LT.JMIN) GO TO 10
168      IF(IBR.EQ.1.AND.XLST.LE.XLAST) GO TO 10
169      IF(IBR.EQ.1.AND.XLST.GT.XLAST) GO TO 60
170      U2 = U2W
171      XSAV = XLST
172      A2 = ALST
173      RHO2 = RHO
174      CAPJ2 = J
175      T2 = T2W
176      P2 = P
177      RSTAR2 = RSTAR
178      OUMC = OUTHAC(NOUT)
179      DO 50 IJ=1,10
180          SIG2(IJ) = SIGMA(IJ)
181      50 CONTINUE
182          SIG2(11) = SIG
183          IBR = 1
184          GO TO 10
185      60 CONTINUE
186          DO 70 IJ=1,10
187              SIGMA(IJ) = SIG2(IJ)
188      70 CONTINUE
189          SIG = SIG2(11)
190          X2 = XSAV
191          IF(SWPO.EQ.1) CALL PRTOU(2,0)
192          RETURN
193      END
```

```

1      SUBROUTINE PART3
2
3      C
4      C      NUCLEATION AND DROPLET GROWTH
5      C
6      COMMON/COEFCO/COEF(10,8,2)
7      COMMON/GAMOUT/GAMBAR
8      DIMENSION HLI(400),SLI(400),YIJ(400)
9      COMMON/SIGCOM/SIGMA(10),SIG,PSUPD
10     COMMON/EQCOM/DELTAT,CAPL,NU,PSI,DRDT,
11     1 TR,LTILDA,KN,THETA,LAMBDA,PR,XI,OMEGA,CAPLAM
12     REAL NU,LTILDA,KN,LAMBDA
13     COMMON/INPT/TO,PO,XLAST,PHI1,RHC,RNO
14     COMMON/SWITCH/SWEND,SWPO,SWG0
15     INTEGER SWEND,SWPO,SWG0
16     COMMON/OUT2/U2,RHO2,CAPJ2,TZ,P2,RSTAR2,X2,A2,SIG2(11),OUMC
17     COMMON/CMOUT3/NENT
18     COMMON/CUT1/50,HO,MDOOT,RHOSTR,TSTAR
19     REAL MDOOT
20     COMMON/CMOUT1/NENTRY,DT,RHOO,T1,H1,U1,USTAR,URHO,RHOF1
21     DIMENSION SIGMSV(10)
22     COMMON/ADJUST/GAMMA1,QC,ALPHA,BETA,DSTAR,ASTAR,DT2,
23     1 JMIN,DELX,EPS(8),IOUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
24     REAL JMIN
25     COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
26     REAL K,M1
27     COMMON I,J,A(400),X(400),DELN(400),CAPJX(400),R(400),
28     1 MU(400),TL(400),T(400),P(400),RSTAR(400),
29     2 U(400),S(400),SL(400),HL(400),RHO(400),CAPJY(400),
30     3 F(400),G(400),YS(400),DELY(400),DELS(400),
31     4 RPERM(400),TS(400),OUTMCH(400),CAPPJ(400)
32     REAL MU
33     REAL LBAR
34     DIMENSION INDTYP(400)
35
36     C
37     C      1 FORMAT(' ***** PROGRAM STOP... EXCESSIVE LOOPING *****')
38     C      2 FORMAT(1H0,' BEFORE DBLIT')
39     C      3 FORMAT(1H , 'J,TOLD,T(J+1),P(J+1)',15,3E16.8)
40     C      4 FORMAT(' RSTAR(J+1),CAPJ-(J),CAPJ+(J)',3E16.8)
41     C      5 FORMAT(' DELN(J),U(J+1),TS(J+1),CP1(J+1)',4E16.8)
42     C      6 FORMAT(' F(J+1),G(J+1),YS(J+1),DELY(J)',4E16.8)
43     C      7 FORMAT(' HL(J+1),SL(J+1),DELS(J),S(J+1)',4E16.8)
44     C      8 FORMAT(' RHO(J+1),A(J+1)',2E16.8)
45     C      9 FORMAT(' (R(I,J+1),I=1,J)',6E16.8)
46     C     10 FORMAT(' (TL(I,J+1),I=1,J)',6E16.8)
47     C     11 FORMAT(' (SL(I,J+1),I=1,J)',6E16.8)
48     C     12 FORMAT(' (HL(I,J+1),I=1,J)',6E16.8)
49     C     13 FORMAT(' (Y(I,J+1),I=1,J)',6E16.8)
50     C     14 FORMAT(1H0,' AFTER DBLIT')
51     C     MAXJ = 1000
52     C     JTOP = MAXJ
53     C     DO 20 IJ=1,400
54     C     RPERM(IJ) = 0.
55     C     20 CONTINUE
56
57     C
58     C      TAKE VALUES FROM PART 2 AS A STARTING POINT
59     C
60     C      T(1) = TZ
61     C      P(1) = P2
62     C      RHO(1) = RHO2
63     C      U(1) = U2
64     C      S(1) = S0
65     C      A(1) = A2
66     C      OUTMCH(1) = OUMC
67     C      X(1) = X2
68     C      RSTAR(1) = RSTAR2
69     C      YS(1) = 0.
70
71     C
72     C      CHEMICAL COMPOSITION REMAINS CONSTANT THROUGHOUT
73     C      PART 3 EXCEPT FOR FORMATION OF LIQUID WATER
74     C      SAVE PART 2 RESULTS
75
76     C
77     C      DO 30 IJ=1,10
78     C      SIGMSV(IJ) = SIGMA(IJ)
79     C      30 CONTINUE
80     C      SIGSV = SIG
81     C      J = 1
82     C      ICHG = 0
83     C      40 CONTINUE
84     C      T(J+1) = T(J)
85     C      P(J+1) = P(J)
86
87     C
88     C      EQUATION (18)

```

```

83      C
84      DO 50 IJK=2,10
85      SIGMA(IJK) = SIGMSV(IJK)/(1. - YS(J))
86      50 CONTINUE
87      C
88      C      EQUATION (17)
89      C
90      SIGMA(1) = SIGMSV(1) - YS(J)/0.018
91      SIGMA(1) = SIGMA(1)/(1. - YS(J))
92      SIG = SIGSV - YS(J)/0.018
93      SIG = SIG/(1. - YS(J))
94      CALL SATTEM(TS(J+1),P(J+1))
95      U(J+1) = U(J)
96      C
97      C      INCREASE THE SIZE OF DELTA X FOR POSITIONS 20
98      C      STEPS PAST THE DROPLET FORMATION CUTOFF
99      C
100     IF(ICHG.LT.15.AND.(J-20).GT.MAXJ) DELX = 1.08*DELX
101     IF((J-20).GT.MAXJ) ICHG = ICHG + 1
102     C
103     C      INCREASE X BY DELTA X, EQUATION (106)
104     C
105     X(J+1) = X(J) + DELX
106     C
107     C      IF AT END OF NOZZLE, CALCULATION IS FINISHED
108     C
109     IF(X(J+1).GT.XLAST) GO TO 240
110     FRCBND = 1.
111     IF(J.EQ.1) GO TO 60
112     FRCBND = (X(J) - X(J-1))/(X(J+1) - X(J))
113     60 CONTINUE
114     C
115     C      GET THE CROSS SECTIONAL AREA FOR THE NEW
116     C      X POSITION, EQUATION (107)
117     C
118     CALL AVSX(X(J+1),A(J+1))
119     CALL SATTEM(TS(J),P(J))
120     PINF = EXPP(55.897 - 6641.7/T(J) - 4.4864*ALOG(T(J)))
121     PBAR = (P(J)/PINF)*(SIGMA(1)/SIG)
122     TR = T(J)/TC
123     SIGMAX = (82.27 + 75.612*TR - 256.889*TR**2 + 95.928*TR**3)
124     1 *1.E-3
125     RSTAR(J) = 2.*SIGMAX/(RHOL*RBAR*T(J)*ALOG(PBAR))
126     R(J) = 1.001*RSTAR(J)
127     CALL GRLPRP
128     IF(J.NE.1) GO TO 80
129     CALL AVSX(X(1)-DELX,AJM)
130     CAPGAM = MDOT/AJM
131     TAUOLD = T(J)
132     70 CONTINUE
133     CALL CDEN(RHOF,SO,TAUOLD)
134     CALL CHG(TAUOLD,HGF,DUM)
135     CALL CCP(TAUOLD,CP,CP1,CPC)
136     UF = SORT(2.*(H0 - HGF))
137     FF = RHOF*UF - CAPGAM
138     DRHODT = (CP - CAPR*SIG)*RHOF/TAUOLD
139     DUDT = -CP/UF
140     FFP = UF*DRHODT + RHOF*DUDT
141     TAUNEW = TAUOLD - FF/FFP
142     DEL = ABS(TAUNEW-TAUOLD)/TAUNEW
143     TAUOLD = TAUNEW
144     IF(DEL.GT.EPS(6)) GO TO 70
145     TJM1 = TAUNEW
146     PJM1 = RHOF*CAPR*SIG*TAUNEW
147     GO TO 90
148     80 CONTINUE
149     TJM1 = T(J-1)
150     PJM1 = P(J-1)
151     90 CONTINUE
152     TJM1 = (TJM1 + (FRCBND - 1.)*T(J))/FRCBND
153     PJM1 = (PJM1 + (FRCBND - 1.)*P(J))/FRCBND
154     TJM = 0.5*(TJM1 + T(J))
155     PJM = 0.5*(PJM1 + P(J))
156     C
157     C      GET NUCLEATION RATE AT J - 1/2
158     C
159     CALL NUCRAT(CAPJX(J),TJM,PJM)
160     DO 100 I=1,J
161     RPERM(I) = R(I)
162     100 CONTINUE
163     NLOOP = 0
164     110 CONTINUE
165     NLOOP = NLOOP + 1
166     IF(NLOOP.GT.400) WRITE(6,1)

```

```

167      IF(NLOOP.GT.400) GO TO 240
168      TJP = 0.5*(T(J) + T(J+1))
169      PJP = 0.5*(P(J) + P(J+1))
170      C
171      C      GET NUCLEATION RATE AT J + 1/2
172      C
173      CALL NUCRAT(CAPJY(J),TJP,PJP)
174      DELN(J) = 0.
175      CAPPJ(J) = 0.
176      IF(CAPJY(J).LT.1.) GO TO 120
177      IF(CAPJX(J).LT.1.) GO TO 120
178      C
179      C      CALCULATE MEAN NUCLEATION RATE, EQUATION (108)
180      C
181      CAPPJ(J) = (CAPJY(J) - CAPJX(J))/ALOG(CAPJY(J)/CAPJX(J))
182      C
183      C      CALCULATE NUMBER OF DROPLETS FORMED, EQUATION (109)
184      C
185      DELN(J) = CAPPJ(J)*A(J)*DELX/MDOT
186      120 CONTINUE
187      C
188      C      SET FLAG TO INDICATE DROPLET FORMATION HAS STOPPED
189      C
190      IF(DELN(J).EQ.0..AND.MAXJ.EQ.1000) MAXJ = J
191      C
192      C      CALCULATE R* FOR DROPLET GROWTH
193      C      EQUATIONS (57) - (59)
194      C
195      PINF = EXPP(55.897 - 6641.7/T(J+1) - 4.4864*ALOG(T(J+1)))
196      PBAR = (P(J+1)/PINF)*(SIGMA(1)/SIG)
197      TR = T(J+1)/TC
198      SIGMAX = (82.27 + 75.612*TR - 256.889*TR**2 + 95.928*TR**3)
199      1 *1.E-3
200      RSTAR(J+1) = 2.*SIGMAX/(RHOL*RBAK*T(J+1)*ALOG(PBAR))
201      C
202      C      CALCULATE THE TIME STEP CORRESPONDING TO THIS
203      C      DELTA X, EQUATION (110)
204      C
205      DELTAT = 2.*DELX/(U(J) + U(J+1))
206      DO 130 I=1,J
207      R(I) = RPERM(I)
208      130 CONTINUE
209      CALL GRLPRP
210      DO 140 I=1,J
211      IF(NLOOP.EQ.1) INDTP(I) = 27
212      140 CONTINUE
213      C
214      C      SET DROPLET RADIUS TO ZERO FOR POSITIONS PAST
215      C      THE DROPLET FORMATION CUTOFF
216      C
217      IF(J.GT.MAXJ) R(J) = 0.
218      JTOP = J
219      IF(J.GT.MAXJ) JTOP = MAXJ
220      DO 160 I=1,JTOP
221      IF(R(I)/RSTAR(J).LT.1.1.AND.NLOOP.EQ.1) INDTP(I) = 26
222      IF(INDTP(I).EQ.26) GO TO 150
223      Z = 1.0001
224      C
225      C      CALCULATE DROPLET GROWTH FOR LARGE
226      C      DROPLETS, EQUATION (72)
227      C
228      IF(NLOOP.EQ.1)
229      1CALL GRL(Z)
230      IF(NLOOP.EQ.1)
231      1R(I) = Z*RSTAR(J)
232      IF(NLOOP.EQ.1) RPERM(I) = R(I)
233      GO TO 160
234      150 CONTINUE
235      IF(R(I).EQ.0.) GO TO 160
236      Z = R(I)/RSTAR(J)
237      C
238      C      CALCULATE DROPLET GROWTH FOR SMALL
239      C      DROPLETS, EQUATION (79)
240      C
241      ZZ = GRS(Z)
242      IF(ZZ.LT.0.) ZZ=0.
243      R(I) = ZZ*RSTAR(J+1)
244      160 CONTINUE
245      R(J+1) = 1.001*RSTAR(J+1)
246      RHO(J+1) = P(J+1)/(CAPR*SIG*T(J+1))
247      F(J+1) = 0.
248      JPI = JTOP + 1
249      CALL NUCRAT(CAPJP1,T(J+1),P(J+1))
250      DELN(J+1) = A(J+1)*DELX*CAPJP1/MDOT

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

251      CAPPJ(J+1) = CAPPJ1
252      YS(J+1) = 0.
253      DO 170 I=1,JP1
254      C
255      C      CALCULATE MASS OF DROPLETS FOR TYPE I
256      C
257      MU(I) = (4./3.)*PI*RHOL*R(I)**3
258      C
259      C      CALCULATE MASS RATIO OF LIQUID WATER
260      C      FOR TYPE I, EQUATION (117)
261      C
262      YIJ(I) = MU(I)*DELN(I)
263      C
264      C      CALCULATE TOTAL MASS RATIO OF LIQUID
265      C      WATER, EQUATION (118)
266      C
267      YS(J+1) = YS(J+1) + YIJ(I)
268      170 CONTINUE
269      DELY(J) = YS(J+1) - YS(J)
270      HL(J+1) = 0.
271      SL(J+1) = 0.
272      JPP1 = J + 1
273      DO 200 I=1,JPP1
274      TL(I) = T(J+1)
275      IF(I.GT.JP1) GO TO 200
276      IF(R(I).LT.RSTAR(J+1)) GO TO 190
277      KN = LTILDA/(2.*R(I))
278      DELTA = XI*KN/PR
279      CALL CCP(T(I),CP,CP1,CPC)
280      WAVG = 0.
281      WC = 0.
282      DO 180 IJ=1,10
283      WAVG = WAVG + W(IJ)*SIGMA(IJ)
284      IF(IJ.NE.1) WC = WC + W(IJ)*SIGMA(IJ)
285      180 CONTINUE
286      WAVG = WAVG/SIG
287      WC = WC/(SIG - SIGMA(1))
288      WRAT = W(1)/WAVG
289      Y1 = SIGMA(1)/SIG
290      GAMMA1 = CP1/(CP1 - CAPR/W(1))
291      GAMMAC = CPC/(CPC - CAPR/WC)
292      FFF = Y1*SQRT(WRAT) + (1. - Y1)*SQRT(WC/WAVG)*((GAMMA1/GAMMAC)
293      1*((GAMMAC + 1.)/(GAMMA1 + 1.))*((CPC/CP1)*ALPHAC
294      DELTA = DELTA/(XI*KN/PR +
295      1 FFF/(1. + 2.*BETA*KN))
296      TL(I) = T(J+1) + (1./(1. - NU*DELTA))*
297      1 (1. - RSTAR(J+1)/R(I))*((TS(J+1) - T(J+1)))
298      190 CONTINUE
299      C
300      C      CALCULATE ENTHALPY OF LIQUID, EQUATION (119)
301      C
302      HLI(I) = 4.2E+03*TL(I) - 17.11753658E+06
303      HL(J+1) = HL(J+1) + YIJ(I)*HLI(I)
304      C
305      C      CALCULATE ENTROPY OF LIQUID, EQUATION (120)
306      C
307      SLI(I) = 4.2E+03*ALOG(TL(I)) - 2.001496281E+04
308      SL(J+1) = SL(J+1) + YIJ(I)*SLI(I)
309      200 CONTINUE
310      TJ = 0.5*(T(J+1) + T(J))
311      PJ = 0.5*(P(J+1) + P(J))
312      CALL SATTEM(TSJ,PJ)
313      JZ = 1
314      IF(TSJ.GT.1000.) JZ = 2
315      CALL CHG(TSJ,DUM,HGX)
316      LBAR = HGX - 4.2E+3*TSJ + 17.11753658E+6
317      JZ = 1
318      IF(TJ.GE.1000.) JZ = 2
319      CALL CCP(TJ,DUM,CP2,DUM)
320      C
321      C      CALCULATE CHANGE IN ENTROPY, EQUATION (83)
322      C
323      DELS(J) = (LBAR - CP2*(TSJ - TJ))*DELY(J)
324      1*(1./TJ - 1./TSJ)
325      C
326      C      CALCULATE ENTROPY OF THE MIXTURE, EQUATION (124)
327      C
328      S(J+1) = S(J) + DELS(J)
329      TOLD = T(J+1)
330      IF(J.LT.JDB) GO TO 210
331      WRITE(6,2)
332      WRITE(6,3) J,TOLD,T(J+1),P(J+1)
333      WRITE(6,4) RSTAR(J+1),CAPPJ(J),CAPPJ(J)
334      WRITE(6,5) DELN(J),U(J+1),TS(J+1),CP1

```

```

335      WRITE(6,6) F(J+1),G(J+1),YS(J+1),DELY(J)
336      WRITE(6,7) HL(J+1),SL(J+1),DELS(J),S(J+1)
337      WRITE(6,8) RHO(J+1),A(J+1)
338      WRITE(6,9) (R(IJK),IJK=1,J)
339      WRITE(6,10) (TL(IJK),IJK=1,J)
340      WRITE(6,11) (SLI(IJK),IJK=1,J)
341      WRITE(6,12) (HLI(IJK),IJK=1,J)
342      WRITE(6,13) (YIJ(IJK),IJK=1,J)
343      210 CONTINUE
344      CALL DBLIT
345      CALL CCP(T(J+1),CPS,CP1,CPC)
346      GAMMAS = CP1/(CP1 - CAPR/W(1))
347      OUTMCH(J+1) = GAMMAS*CAPR*SIG*T(J+1)
348      OUTMCH(J+1) = U(J+1)/SQRT(OUTMCH(J+1))
349      IF(J.LT.JDB) GO TO 220
350      WRITE(6,14)
351      WRITE(6,3) J,TOLD,T(J+1),P(J+1)
352      WRITE(6,4) RSTAR(J+1),CAPJX(J),CAPJY(J)
353      WRITE(6,5) DELN(J),U(J+1),TS(J+1),CP1
354      WRITE(6,6) F(J+1),G(J+1),YS(J+1),DELY(J)
355      WRITE(6,7) HL(J+1),SL(J+1),DELS(J),S(J+1)
356      WRITE(6,8) RHO(J+1),A(J+1)
357      WRITE(6,9) (R(IJK),IJK=1,J)
358      WRITE(6,10) (TL(IJK),IJK=1,J)
359      WRITE(6,11) (SLI(IJK),IJK=1,J)
360      WRITE(6,12) (HLI(IJK),IJK=1,J)
361      WRITE(6,13) (YIJ(IJK),IJK=1,J)
362      220 CONTINUE
363      C
364      C      CONVERGENCE TEST
365      C
366      DEL = (T(J+1) - TOLD)/TOLD
367      TOLD = T(J+1)
368      C
369      C      TEST FOR TEMPERATURE CONVERGENCE EQUATION (133)
370      C      IF NO CONVERGENCE GO BACK TO DROPLET GROWTH
371      C
372      IF(ABS(DEL).GT.EPS(7)) GO TO 110
373      C
374      C      CONVERGENCE...OUTPUT RESULTS AND GO ON
375      C      TO THE NEXT VALUE OF J
376      C
377      WRITE(7) J,(R(I),MU(I),HLI(I),SLI(I),TL(I),YIJ(I),I=1,J)
378      GAMBAR = ALOG(T(J+1)/T0)/ALOG(P(J+1)/P0)
379      GAMBAR = 1./(1. - GAMBAR)
380      IF(1OUT.EQ.2.AND.SWPO.EQ.1) CALL PRTOUT(3,1)
381      DO 230 I=1,J
382      IF(INDTYP(I).EQ.26) RPERM(I) = R(I)
383      230 CONTINUE
384      GAMBAR = ALOG(T(J+1)/T0)/ALOG(P(J+1)/P0)
385      GAMBAR = 1./(1. - GAMBAR)
386      WRITE(33) J,x(J),DELN(J),(R(KK),KK=1,J)
387      J = J + 1
388      C
389      C      IF AT TERMINAL J, CALCULATION IS FINISHED
390      C
391      IF(J.GT.JSTOP) GO TO 240
392      GO TO 40
393      240 CONTINUE
394      IF(SWPO.EQ.1) CALL PRTOUT(3,0)
395      RETURN
396      END

```



```

1      SUBROUTINE PLTOUT
2
3      C      SUBROUTINE PLTOUT GENERATES PLOT OUTPUT OF PROGRAM
4      C      RESULTS. SEVERAL SUPPORTING SUBROUTINES ARE A PART
5      C      OF THE LANGLEY GRAPHICS SYSTEM. THESE INCLUDE:
6      C      ASCALE
7      C      AXES
8      C      CALPLT
9      C      CHARST3
10     C      CHARST4
11     C      CHARS12
12     C      DASHPLT
13     C      LINPLT
14     C      NFRAME
15     C      NOTATE
16     C      PNTPLT
17     C      REPCAR
18     C      FOR MORE INFORMATION ON THESE ROUTINES SEE "LANGLEY
19     C      GRAPHICS SYSTEM", CENTRAL SCIENTIFIC COMPUTING COMPLEX
20     C      DOCUMENT G-3.
21     C
22     COMMON I,J,A(400),X(400),DELN(400),CAPJX(400),R(400),
23     1 MU(400),TL(400),T(400),P(400),RSTAR(400),
24     2 U(400),S(400),SL(400),HL(400),RHO(400),CAPJY(400),
25     3 F(400),G(400),YS(400),DELY(400),DELS(400),
26     4 RPERM(400),TS(400),OUTMCH(400),CAPPJ(400)
27     REAL MU
28     COMMON/OUT1/50,H0,MDOOT,RHOSTR,TSTAR
29     REAL MDOOT
30     DIMENSION DUM(400)
31     COMMON/SVX2/X22,Y22
32     COMMON/EXPDAT/NEXP,XEXP(50),PEXP(50),PREF
33     COMMON/PLTBLK/XMIN,XMAX,PMIN,PMAX,TMIN,TMAX,
34     1 YMIN,YMAX,DTMIN,DTMAX,DNMIN,DNMAX,RMIN,RMAX,
35     2 PRMIN,PRMAX,TLMIN,TLMAX,RHOMIN,RHOMAX,
36     3 SMIN,SMAX,UMIN,UMAX,XMIN,XMAX,IPSLCT(15)
37     COMMON/INPT/T0,P0,XLAST,PHI1,RHC,RND
38     COMMON/PLTOUT/NOUT,TOUT(600),POUT(600),XOUT(600),
39     1 DELTT(600),UOUT(600),OUTMAC(600)
40     DIMENSION YP(400)
41     DIMENSION PAT(2)
42     DIMENSION PATX(4),PATY(4)
43     DATA PAT/0.5,-0.25/
44     DATA PATX/0.,1.25,0.,1./
45     DATA PATY/0.58,0.58,0.,1./
46
47     C      CALL CHARS12
48     CALL REPCAR(2,12)
49     CALL CHARST4
50     CALL CHARST3
51     NP = J - 1
52     XSV = X(1)
53     X(1) = 0.
54     CALL ASCALE(X,8.,NP,1,10.)
55     IF(XMIN.NE.0..OR.XMAX.NE.0.) X(NP+1) = XMIN
56     IF(XMIN.NE.0..OR.XMAX.NE.0.) X(NP+2) = (XMAX - XMIN)/8.
57     XOUT(NOUT+1) = X(NP+1)
58     XOUT(NOUT+2) = X(NP+2)
59     X(1) = XSV
60     IF(IPSLCT(2).EQ.0) GO TO 40
61
62     C      PRESSURE RATIO VS X
63     C
64     NOUTM = NOUT - 1
65     DO 30 IJ=1,NP
66     DO 10 IJK=1,NOUTM
67     IF(X(IJ).GE.XOUT(IJK).AND.X(IJ).LE.XOUT(IJK+1)) GO TO 20
68     CONTINUE
69     IJK = NOUTM
70     CONTINUE
71     YP(IJ) = POUT(IJK) + (X(IJ) - XOUT(IJK))
72     1 *(POUT(IJK+1) - POUT(IJK))/(XOUT(IJK+1) - XOUT(IJK))
73     YP(IJ) = P(IJ)/(YP(IJ)*P0)
74     30 CONTINUE
75     CALL ASCALE(YP,6.,NP,1,10.)
76     IF(PRMIN.NE.0..OR.PRMAX.NE.0) YP(NP+1) = PRMIN
77     IF(PRMIN.NE.0..OR.PRMAX.NE.0) YP(NP+2) = (PRMAX - PRMIN)/6.
78     CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
79     1 IHX,0.2,-1)
80     CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
81     1 7HP,RATIO,0.2,7)
82     CALL LINPLT(X,YP,NP,1,0,0,0,0)

```

```

83      XPLT = (X22 - X(NP+1))/X(NP+2)
84      YPLT = 0.
85      CALL PNTPLT(XPLT,YPLT,4,1)
86      CALL NFRAME
87      CALL CALPLT(4.5,1.5,-3)
88      40 IF(IPSLECT(7).EQ.0) GO TO 60
89      C
90      C      CRITICAL RADIUS VS X
91      C
92      DO 50 IJ=1,NP
93      YP(IJ) = RSTAR(IJ)
94      50 CONTINUE
95      CALL ASCALE(YP,6.,NP,1,10.)
96      IF(RMIN.NE.0..OR.RMAX.NE.0.) YP(NP+1) = RMIN
97      IF(RMIN.NE.0..OR.RMAX.NE.0.) YP(NP+2) = (RMAX-RMIN)/6.
98      CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
99      1 1HX,0.2,-1)
100     CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
101     1 5HRSTAR,0.2,5)
102     CALL LINPLT(X,YP,NP,1,0,0,0,0)
103     CALL NFRAME
104     CALL CALPLT(4.5,1.5,-3)
105     60 IF(IPSLECT(8).EQ.0) GO TO 140
106     C
107     C      DROPLET RADIUS (AND R*) VS X
108     C
109     NRAD = NP/10
110     NRAD = NRAD - 1
111     IF(NRAD.GT.10) NRAD = 10
112     IRAD = 5
113     DO 120 JRAD=1,NRAD
114     REWIND 7
115     70 CONTINUE
116     READ(7,END=80) JJJ,(DUM(IJ),DUM1,DUM2,DUM3,DUM4,DUM5,IJ=1,JJJ)
117     80 IF(EOF(7).NE.0) GO TO 90
118     IF(JJJ.LT.IRAD) GO TO 70
119     YP(JJJ) = DUM(IRAD)
120     GO TO 70
121     90 CONTINUE
122     NPP = NP - IRAD + 2
123     YP(IRAD-1) = 0.
124     DO 100 IJ=1,NPP
125     KRAD = IRAD + IJ - 2
126     IF(YP(KRAD).LE.10.**RMIN) YP(KRAD) = 10.**RMIN
127     YP(KRAD) = ALOG10(YP(KRAD))
128     100 CONTINUE
129     IF(JRAD.EQ.1) CALL ASCALE(YP(IRAD-1),6.,NPP,1,10.)
130     IF(JRAD.NE.1) GO TO 110
131     IF(RMIN.NE.0..OR.RMAX.NE.0.) YP(NP+1) = RMIN
132     IF(RMIN.NE.0..OR.RMAX.NE.0.) YP(NP+2) = (RMAX-RMIN)/6.
133     110 CONTINUE
134     IF(JRAD.EQ.1)
135     1CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
136     1 'D(ISTANCE )A(LONG )N(OZZLE X, M)',0.2,-32)
137     IF(JRAD.EQ.1)
138     1CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.5,0.,
139     2 'D(ROPLET )R(RADIUS, $2L$30G R$UI$N AND $2L$30G R$D*$N, M',
140     3 0.2,55)
141     NPP = NPP - 1
142     IF(YP(IRAD).NE.RMIN) YP(IRAD) = ALOG10(RSTAR(IRAD))
143     CALL LINPLT(X,YP,IRAD,NPP,1,0,0,0,0)
144     IRAD = IRAD + 10
145     120 CONTINUE
146     DO 130 IJ=1,NP
147     YP(IJ) = RSTAR(IJ)
148     IF(YP(IJ).LE.10.**RMIN) YP(IJ) = 10.**RMIN
149     YP(IJ) = ALOG10(YP(IJ))
150     130 CONTINUE
151     CALL LINPLT(X,YP,NP,1,0,0,0,0)
152     CALL NFRAME
153     CALL CALPLT(4.5,1.5,-3)
154     140 IF(IPSLECT(9).EQ.0) GO TO 280
155     C
156     C      TEMPERATURE OF LIQUID VS X
157     C
158     DO 150 IJ=1,NP
159     YP(IJ) = TS(IJ)
160     150 CONTINUE
161     NRAD = NP/10
162     NRAD = NRAD - 1
163     IF(NRAD.GT.10) NRAD = 10
164     IRAD = 5
165     DO 200 JRAD=1,NRAD
166     REWIND 7

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

167      160 CONTINUE
168      READ(7,END=170) JJJ,(DUM4,DUM1,DUM2,DUM3,DUM(IJ),DUM5,IJ=1,JJJ)
169      170 IF(EOF(7).NE.0) GO TO 180
170      IF(JJJ.LT.IRAD) GO TO 160
171      YP(JJJ) = DUM(IRAD)
172      GO TO 160
173      180 CONTINUE
174      NPP = NP - IRAD + 2
175      YP(IRAD-1) = 0.
176      IF(JRAD.EQ.1) CALL ASCALE(YP(IRAD-1),6.,NPP,1,10.)
177      IF(JRAD.NE.1) GO TO 190
178      IF(TLMIN.NE.0..OR.TLMAX.NE.0.) YP(NP+1) = TLMIN
179      IF(TLMIN.NE.0..OR.TLMAX.NE.0.) YP(NP+2) = (TLMAX - TLMIN)/6.
180      190 CONTINUE
181      IF(JRAD.EQ.1)
182      1CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
183      1 IHX,0.2,-1)
184      IF(JRAD.EQ.1)
185      1CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
186      1 IHT,0.2,1)
187      NPP = NPP - 1
188      CALL LINPLT(X,YP,NP,1,0,0,0,0)
189      IRAD = IRAD + 10
190      200 CONTINUE
191      DO 210 IJ=1,NP
192      YP(IJ) = T(IJ)
193      210 CONTINUE
194      CALL LINPLT(X,YP,NP,1,0,0,0,0)
195      DO 220 IJ=1,NOUT
196      TOUT(IJ) = TOUT(IJ)*T0
197      220 CONTINUE
198      CMAX = YP(NP+1) + 6.*YP(NP+2)
199      DO 230 IJ=1,NOUT
200      IF(TOUT(IJ).LE.CMAX) GO TO 240
201      230 CONTINUE
202      IJ = 1
203      240 IBEG = IJ
204      DO 250 IJ=1,NOUT
205      IF(XOUT(IJ).GE.20.) GO TO 260
206      250 CONTINUE
207      IJ = NOUT
208      IEND = IJ
209      NOUTX = IEND - IBEG + 1
210      TSAVE1 = TOUT(IEND+1)
211      TSAVE2 = TOUT(IEND+2)
212      TOUT(IEND+1) = YP(NP+1)
213      TOUT(IEND+2) = YP(NP+2)
214      TMP5 = XOUT(IEND+1)
215      TMP6 = XOUT(IEND+2)
216      XOUT(IEND+1) = XOUT(NOUT+1)
217      XOUT(IEND+2) = XOUT(NOUT+2)
218      CALL DASHPLT(XOUT(IBEG),TOUT(IBEG),NOUTX,1,PAT,2)
219      XOUT(IEND+1) = TMP5
220      XOUT(IEND+2) = TMP6
221      TOUT(IEND+1) = TSAVE1
222      TOUT(IEND+2) = TSAVE2
223      DO 270 IJ=1,NOUT
224      TOUT(IJ) = TOUT(IJ)/T0
225      270 CONTINUE
226      CALL NFRAME
227      CALL CALPLT(4.5,1.5,-3)
228      280 IF(IPSLCT(10).EQ.0) GO TO 300
229      C
230      DENSITY VS X
231      C
232      DO 290 IJ=1,NP
233      YP(IJ) = RHO(IJ)
234      290 CONTINUE
235      CALL ASCALE(YP,6.,NP,1,10.)
236      IF(RHOMIN.NE.0..OR.RHOMAX.NE.0.) YP(NP+1) = RHOMIN
237      IF(RHOMIN.NE.0..OR.RHOMAX.NE.0.) YP(NP+2) = (RHOMAX - RHOMIN)/6.
238      CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
239      1 IHX,0.2,-1)
240      CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
241      1 3HRHO,0.2,3)
242      CALL LINPLT(X,YP,NP,1,0,0,0,0)
243      CALL NFRAME
244      CALL CALPLT(4.5,1.5,-3)
245      300 IF(IPSLCT(13).EQ.0) GO TO 340
246      C
247      MACH NUMBER VS X
248      C
249      CALL ASCALE(OUTMAC,6.,NOUT,1,10.)
250      IF(XMMIN.NE.0..OR.XMMAX.NE.0.) OUTMAC(NOUT+1) = XMMIN

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

251      IF(XMMIN.NE.0..OR.XMMAX.NE.0.) OUTMAC(NOUT+2) = (XMMAX - XMMIN)/6.
252      CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
253      1 1HX,0.2,-1)
254      CALL AXES(0.,0.,90.,6.,OUTMAC(NOUT+1),OUTMAC(NOUT+2),1.,0.,
255      1 4HMACH,0.2,4)
256      DO 310 IJ=1,NOUT
257      IF(OUTMAC(IJ).GE.OUTMAC(NOUT+1)) GO TO 320
258 310 CONTINUE
259      IJ = 1
260 320 NOUTX = NOUT - IJ + 1
261      CALL LINPLT(XOUT(IJ),OUTMAC(IJ),NOUTX,1,0,0,0,0)
262      DO 330 IJ=1,NP
263      YP(IJ) = OUTMCH(IJ)
264 330 CONTINUE
265      YP(NP+1) = OUTMAC(NOUT+1)
266      YP(NP+2) = OUTMAC(NOUT+2)
267      CALL LINPLT(X,YP,NP,1,0,0,0,0)
268      CALL NFRAME
269      CALL CALPLT(4.5,1.5,-3)
270 340 IF(IPSLCT(1).EQ.0.AND.IPSLCT(14).EQ.0) GO TO 400
271 C
272 C      NORMALIZED PRESSURE VS X
273 C
274      DO 350 IJ=1,NP
275      YP(IJ) = P(IJ)/PO
276 350 CONTINUE
277      TMP1 = YP(NP)
278      YP(NP) = AMIN1(P(NP)/PO,POUT(NOUT))
279      CALL ASCALE(YP,6.,NP,1,10.)
280      IF(PMIN.NE.0..OR.PMAX.NE.0.) YP(NP+1) = PMIN
281      IF(PMIN.NE.0..OR.PMAX.NE.0.) YP(NP+2) = (PMAX-PMIN)/6.
282      YP(NP) = TMP1
283      CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
284      1 'D(ISTANCE )A(LONG )N(OZZLE X, M)',0.2,-32)
285      CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
286      1 'N(ORMALIZED )S(TATIC )P(RESSURE, P/P$DO)',
287      2 0.2,40)
288      CALL LINPLT(X,YP,NP,1,0,0,0,0)
289      TMP1 = X(NP+1)
290      TMP2 = X(NP+2)
291      TMP3 = YP(NP+1)
292      TMP4 = YP(NP+2)
293      XOUT(NOUT+1) = TMP1
294      XOUT(NOUT+2) = TMP2
295      POUT(NOUT+1) = TMP3
296      POUT(NOUT+2) = TMP4
297      CMAX = YP(NP+1) + 6.*YP(NP+2)
298      DO 360 IJ=1,NOUT
299      IF(POUT(IJ).LE.CMAX) GO TO 370
300 360 CONTINUE
301      IJ = 1
302 370 NOUTX = NOUT - IJ + 1
303      CALL DASHPLT(XOUT(IJ),POUT(IJ),NOUTX,1,PAT,2)
304      IF(NEXP.EQ.0) GO TO 390
305      DO 380 IJ=1,NEXP
306      XPLOT = XEXP(IJ)/39.37
307      XPLOT = (XPLOT - X(NP+1))/X(NP+2)
308      YPLOT = PEXP(IJ)/PREF
309      YPLOT = (YPLOT - YP(NP+1))/YP(NP+2)
310      CALL PNTPLT(XPLOT,YPLOT,1,1)
311 380 CONTINUE
312 390 CONTINUE
313      XPLOT = (X22 - X(NP+1))/X(NP+2)
314      YPLOT = (Y22 - YP(NP+1))/YP(NP+2)
315      CALL PNTPLT(XPLOT,YPLOT,901,1)
316      IF(IPSLCT(14).NE.0) GO TO 400
317      CALL NFRAME
318      CALL CALPLT(4.5,1.5,-3)
319 400 IF(IPSLCT(3).EQ.0.AND.IPSLCT(14).EQ.0) GO TO 440
320 C
321 C      NORMALIZED TEMPERATURE VS X
322 C
323      DO 410 IJ=1,NP
324      YP(IJ) = T(IJ)/TO
325 410 CONTINUE
326      TMP1 = YP(NP)
327      YP(NP) = AMIN1(T(NP)/TO,TOUT(NOUT))
328      CALL ASCALE(YP,6.,NP,1,10.)
329      IF(TMIN.NE.0..OR.TMAX.NE.0.) YP(NP+1) = TMIN
330      IF(TMIN.NE.0..OR.TMAX.NE.0.) YP(NP+2) = (TMAX-TMIN)/6.
331      YP(NP) = TMP1
332      IF(IPSLCT(3).NE.0)
333      1CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
334      1 1HX,0.2,-1)

```

```

335      IF(IPSLECT(3).NE.0)
336      1CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
337      1 4HT/TO,0.2,4)
338      IF(IPSLECT(14).NE.0)
339      1CALL AXES(-1.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
340      1 4HT/TO,0.2,4)
341      CALL LINPLT(X,YP,NP,1,0,0,0,0)
342      TMP1 = X(NP+1)
343      TMP2 = X(NP+2)
344      TMP3 = YP(NP+1)
345      TMP4 = YP(NP+2)
346      XOUT(NOUT+1) = TMP1
347      XOUT(NOUT+2) = TMP2
348      TOUT(NOUT+1) = TMP3
349      TOUT(NOUT+2) = TMP4
350      CMAX = YP(NP+1) + 6.*YP(NP+2)
351      DO 420 IJ=1,NOUT
352      IF(TOUT(IJ).LE.CMAX) GO TO 430
353      420 CONTINUE
354      IJ = 1
355      430 NOUTX = NOUT - IJ + 1
356      CALL LINPLT(XOUT(IJ),TOUT(IJ),NOUTX,1,0,0,0,0)
357      IF(IPSLECT(14).NE.0) GO TO 440
358      CALL NFRAME
359      CALL CALPLT(4.5,1.5,-3)
360      440 IF(IPSLECT(12).EQ.0.AND.IPSLECT(14).EQ.0) GO TO 510
361      C
362      C      FLOW VELOCITY VS X
363      C
364      DO 450 IJ=1,NP
365      YP(IJ) = U(IJ)
366      450 CONTINUE
367      CALL ASCALE(YP,6.,NP,1,10.)
368      IF(UMIN.NE.0..OR.UMAX.NE.0.) YP(NP+1) = UMIN
369      IF(UMIN.NE.0..OR.UMAX.NE.0.) YP(NP+2) = (UMAX - UMIN)/6.
370      UOUT(NOUT+1) = YP(NP+1)
371      UOUT(NOUT+2) = YP(NP+2)
372      IF(IPSLECT(12).NE.0)
373      1CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
374      1 1HX,0.2,-1)
375      IF(IPSLECT(12).NE.0)
376      1CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
377      1 1HU,0.2,1)
378      IF(IPSLECT(14).NE.0)
379      1CALL AXES(-2.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
380      1 1HU,0.2,1)
381      CALL LINPLT(X,YP,NP,1,0,0,0,0)
382      DO 460 IJ=1,NOUT
383      IF(UOUT(IJ).GE.(YP(NP+1)+6.*YP(NP+2))) GO TO 470
384      460 CONTINUE
385      NOUTY = NOUT
386      GO TO 480
387      470 NOUTY = IJ - 1
388      480 CONTINUE
389      DO 490 IJ=1,NOUT
390      IF(UOUT(IJ).GE.YP(NP+1)) GO TO 500
391      490 CONTINUE
392      IJ = 1
393      500 NOUTX = NOUTY - IJ + 1
394      XOUT(NOUTY+1) = XOUT(NOUT+1)
395      XOUT(NOUTY+2) = XOUT(NOUT+2)
396      UOUT(NOUTY+1) = YP(NP+1)
397      UOUT(NOUTY+2) = YP(NP+2)
398      CALL LINPLT(XOUT(IJ),UOUT(IJ),NOUTX,1,0,0,0,0)
399      CALL NFRAME
400      CALL CALPLT(4.5,1.5,-3)
401      510 IF(IPSLECT(4).EQ.0.AND.IPSLECT(15).EQ.0) GO TO 530
402      C
403      C      MASS FRACTION VS X
404      C
405      NPM = NP - 1
406      DO 520 IJ=1,NP
407      YP(IJ) = YS(IJ)
408      520 CONTINUE
409      CALL ASCALE(YP,6.,NP,1,10.)
410      IF(YMIN.NE.0..OR.YMAX.NE.0.) YP(NP+1) = YMIN
411      IF(YMIN.NE.0..OR.YMAX.NE.0.) YP(NP+2) = (YMAX-YMIN)/6.
412      CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
413      2 'D(ISTANCE )A(LONG )N(OZZLE X, M)',0.2,-32)
414      CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
415      1 'M(ASS )F(RACTION OF )L(IQUID )W(ATER, W)',
416      2 0.2,40)
417      CALL LINPLT(X,YP,NP,1,0,0,0,0)
418      IF(IPSLECT(15).NE.0) GO TO 530

```

```

419      CALL NFRAME
420      CALL CALPLT(4.5,1.5,-3)
421 530 IF(IPSLCT(5).EQ.0.AND.IPSLCT(15).EQ.0) GO TO 580
422 C
423      TEMPERATURE DIFFERENCE VS X
424 C
425      DO 540 IJ=1,NP
426      YP(IJ) = TS(IJ) - T(IJ)
427 540 CONTINUE
428      CALL ASCALE(YP,6.,NP,1,10.)
429      IF(DTMIN.NE.0..OR.DTMAX.NE.0.) YP(NP+1) = DTMIN
430      IF(DTMIN.NE.0..OR.DTMAX.NE.0.) YP(NP+2)
431      1 = (DTMAX - DTMIN)/6.
432      IF(IPSLCT(5).NE.0)
433      1CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
434      1 1HX,0.2,-1)
435      IF(IPSLCT(5).NE.0)
436      1CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
437      1 6HDELTAT,0.2,6)
438      IF(IPSLCT(15).NE.0)
439      1CALL AXES(-1.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
440      2 'TEMPERATURE D(IFFERENCE, )TSD(S)N(S(PSD1$N$)-)TSDG$N, K',
441      3 0.2,58)
442      CALL LINPLT(X,YP,NP,1,0,0,0,0)
443      DO 550 IJ=1,NOUT
444      IF(XOUT(IJ).GE.X(1)) GO TO 560
445 550 CONTINUE
446      NOUTX = NOUT
447      GO TO 570
448 560 NOUTX = IJ
449 570 CONTINUE
450      DELTT(NOUTX+1) = YP(NP+1)
451      DELTT(NOUTX+2) = YP(NP+2)
452      XOUT(NOUTX+1)=X(NP+1)
453      XOUT(NOUTX+2)=X(NP+2)
454      CALL LINPLT(XOUT,DELTT,NOUTX,1,0,0,0,0)
455      IF(IPSLCT(15).NE.0) GO TO 580
456      CALL NFRAME
457      CALL CALPLT(4.5,1.5,-3)
458 580 IF(IPSLCT(6).EQ.0.AND.IPSLCT(15).EQ.0) GO TO 610
459 C
460      NUCLEATION RATE VS X
461 C
462      DO 590 IJ=1,NPM
463      YP(IJ) = CAPPJ(IJ)
464 590 CONTINUE
465      CALL ASCALE(YP,6.,NPM,1,10.)
466      IF(DNMIN.NE.0..OR.DNMAX.NE.0.) YP(NP) = DNMIN
467      IF(DNMIN.NE.0..OR.DNMAX.NE.0.) YP(NP+1)
468      1 = (DNMAX - DNMIN)/6.
469      DO 600 IJ=1,NPM
470      IF(YP(IJ).LE.10.**DNMIN) YP(IJ) = 10.**DNMIN
471      YP(IJ) = ALOG10(YP(IJ))
472 600 CONTINUE
473      IF(IPSLCT(6).NE.0)
474      1CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
475      1 1HX,0.2,-1)
476      IF(IPSLCT(6).NE.0)
477      1CALL AXES(0.,0.,90.,6.,YP(NP),YP(NP+1),2.,0.,
478      1 6HLOG(J),0.2,6)
479      IF(IPSLCT(15).NE.0)
480      1CALL AXES(-2.,0.,90.,6.,YP(NP),YP(NP+1),2.,0.,
481      1 'NUCLEATION R(ATE, $2L$30G )J, D(ROPLETS/$$U3$N-S)',
482      2 0.2,51)
483      CALL LINPLT(X(2),YP,NPM,1,0,0,0,0)
484      CALL NFRAME
485      CALL CALPLT(4.5,1.5,-3)
486 610 IF(IPSLCT(11).EQ.0) GO TO 630
487 C
488      ENTROPY PRODUCTION VS X
489 C
490      DO 620 IJ=1,NP
491      YP(IJ) = S(IJ) - 50
492 620 CONTINUE
493      CALL ASCALE(YP,6.,NP,1,10.)
494      IF(SMIN.NE.0..OR.SMAX.NE.0.) YP(NP+1) = SMIN
495      IF(SMIN.NE.0..OR.SMAX.NE.0.) YP(NP+2) = (SMAX - SMIN)/6.
496      IF(IPSLCT(11).NE.0)
497      1CALL AXES(0.,0.,0.,8.,X(NP+1),X(NP+2),1.,0.,
498      2 'D(ISTANCE )A(LONG )N(OZZLE X, M)',0.2,-32)
499      IF(IPSLCT(11).NE.0)
500      1CALL AXES(0.,0.,90.,6.,YP(NP+1),YP(NP+2),1.,0.,
501      1 'E(NTROPY )P(RDUCTION, )$4D$3(S, )J/(KG)-K',
502      2 0.2,42)

```

ORIGINAL PAGE IS
OF POOR QUALITY

```
503 CALL LINPLT(X,YP,NP,1,0,0,0,0)
504 CALL NFRAME
505 CALL CALPLT(4,5,1.5,-3)
506 CALL NOTATE(0.,5.5,0.16,'TSD(S)$N($P$D1$N$)-)TSDG$N',0.,27)
507 CALL NOTATE(0.,4.5,0.16,'J',0.,1)
508 CALL NOTATE(0.,3.5,0.16,'(W)',0.,3)
509 CALL NOTATE(0.,2.5,0.16,'(SATURATION)',0.,12)
510 CALL NOTATE(0.,1.5,0.16,'(R)$D*$N',0.,8)
511 CALL LINPLT(PATX,PATY,2,1,0,0,0,0)
512 CALL NOTATE(1.7,0.5,0.16,'(NUCLEATION AND CONDENSATION)',0.,29)
513 PATY(1) = PATY(1) - 0.5
514 PATY(2) = PATY(2) - 0.5
515 CALL DASHPLT(PATX,PATY,2,1,PAT,2)
516 CALL NOTATE(1.7,0.,0.16,'(ISENTROPIC WITHOUT CONDENSATION)',0.,33)
517 630 CONTINUE
518 RETURN
519 END
```

ORIGINAL PAGE IS
OF POOR QUALITY

SUBROUTINE PRTOUT(IP,IL)

C
C
C
C

SUBROUTINE PRTOUT GENERATES PRINT OUTPUT OF THE
PROGRAM RESULTS

DIMENSION HLI3(400),SLI3(400),YIJ3(400)
COMMON/CMOUT3/NENT
COMMON/GAMOUT/GAMBAR
COMMON/INPT/TO,PO,XLAST,PHI1,RHC,RNO
COMMON I3,J3,A3(400),X3(400),DELN3(400),CAPJX3(400),R3(400),
1 MU3(400),TL3(400),T3(400),P3(400),RSTAR3(400),
2 U3(400),S3(400),SL3(400),HL3(400),RH03(400),
3 CAPJY3(400),F3(400),G3(400),YS3(400),
4 DELY3(400),DELS3(400),RPERM3(400),TS3(400)
5 ,OUTMCH(400),CAPPJ(400)
REAL MU3
COMMON/OUT1/SO,H0,MDOOT,RH0STR,TSTAR
REAL MDOOT
COMMON/CMOUT1/NENTRY,DT,RH00,T1,H1,U1,USTAR,URHO,RHOF1
COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
COMMON/OUT2/U2,RH02,CAPJ2,T2,P2,RSTAR2,X2,A2,SIG2(11),OUMC
COMMON/ADJUST/GAMMA1,QC,ALPHA,BETA,DSTAR,ASTAR,DT2,
1 JMIN,DELX,EPS(8),IOUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
REAL JMIN
COMMON/SWITCH/SWEND,SWPO,SWG0
COMMON/CMOUT2/NE,T2W,SIGMAX,U2W,RH0,P,PINF,PBAR,TR,H2W,RSTAR,CAPL,
1 PHI,J
REAL J
INTEGER SWEND,SWPO,SWG0
DATA N2/0/
DATA IFLG/1/

C

1 FORMAT(1H1,20X,14HPART 1 SUMMARY///
1 1H0,17X,9HSO = ,1PE16.8/
2 1H0,17X,9HHO = ,1PE16.8/
3 1H0,17X,9HMDOT = ,1PE16.8/
4 1H0,17X,9HRHO* = ,1PE16.8/
5 1H0,17X,9HT* = ,1PE16.8/
6 1H0,17X,9HU* = ,1PE16.8/
7 1H0,17X,9HSIGMA = ,1PE16.8/
8 9(1H0,26X,1PE16.8/))
2 FORMAT(1H1,20X,22HPART 1 EXTENDED OUTPUT///
1 1H0,4X,4X,5H A* ,9X,3HHO ,9X,5HRHO0 ,9X,3HSO ,10X,
2 3HRHO,11X,1HT,12X,1HH,12X,1HU,10X,5HU*RH0,8X,6HGAMMA1/
3 FORMAT(3X,10(1PE13.5))
4 FORMAT(1H1,20X,14HPART 2 SUMMARY///
1 1H0,17X,9HU = ,1PE16.8/
2 1H0,17X,9HRHO = ,1PE16.8/
3 1H0,17X,9HJ = ,1PE16.8/
4 1H0,17X,9HT = ,1PE16.8/
5 1H0,17X,9HP = ,1PE16.8/
6 1H0,17X,9HR* = ,1PE16.8/
7 1H0,17X,9HSIGMA = ,1PE16.8/
8 9(1H0,26X,1PE16.8/))
5 FORMAT(1H1,20X,22HPART 2 EXTENDED OUTPUT///
6 FORMAT(
1 1H0,4X,4X,4HT/TO,11X,1HH,12X,1HU,11X,3HRHO,9X,4HP/PO,9X,5H PINF,
2 8X,4HPBAR,11X,1HX,10X,6HGAMMA1)
7 FORMAT(
1 1H ,4X,5X,3H TR,9X,6HSIGMAX,8X,5HRSTAR,10X,1HL,11X,3HPHI,
2 11X,1HJ)
8 FORMAT(1H1,20X,14HPART 3 SUMMARY///
1 1H0,4X,6X,1HX,10X,4HP/PO,9X,4HT/TO,
2 10X,2HJ-,11X,2HJ+,9X,4HDELN,11X,1HU,12X,1HY,10X,4HDELS//
9 FORMAT(1H1,20X,22HPART 3 EXTENDED OUTPUT///
10 FORMAT(14,9(1PE13.5))
11 FORMAT(1H1)
12 FORMAT(/5X,4HJ = ,15,5X,4HX = ,1PE13.5,
2 5X,4HT = ,1PE16.8//7X,2X,1HI,
1 8X,1HR,11X,2HMU,11X,3HHLI,10X,3HSLI,10X,2HTL,10X,3HYIJ//
13 FORMAT(5X,15,6(1PE13.4))
14 FORMAT(5H R = ,1X,9(1PE13.5)/30(6X,9(1PE13.5)/))
15 FORMAT(
1 1H ,2X,1HJ,1X,3X,6HT(J+1),7X,6HP(J+1),7X,6HU(J+1),7X,6HY(J+1),
2 7X,6HS(J+1),7X,7HSL(J+1),6X,7HHL(J+1),6X,6HX(J+1),7X,6HA(J+1))
16 FORMAT(5X,2X,8HRHO(J+1),4X,10HRSTAR(J+1),4X,9H DELY(J) ,
1 4X,9H DELN(J) ,5X,7HTS(J+1),4X,8HCP1(J+1),7X,6HGAMMA1)
17 FORMAT(4X,9(1PE13.5))

C

IF(NENTRY.EQ.1) NLINE = 0
GO TO (20,40,70),IP

C


```

83      C          PART 1 OUTPUT
84      C
85      20 CONTINUE
86      IF(IL.NE.0) GO TO 30
87      C
88      C          STANDARD OUTPUT
89      C
90      WRITE(6,1) SO,H0,MDOOT,RHOSTR,TSTAR,USTAR,SIGMA
91      GO TO 140
92      30 CONTINUE
93      IF(IL.NE.2) GO TO 140
94      C
95      C          DEBUG OUTPUT
96      C
97      IF(NENTRY.EQ.1.OR.NLINE.EQ.0) WRITE(6,2)
98      IF(NLINE.EQ.0) NLINE = 6
99      NLINE = NLINE + 1
100     IF(NLINE.GT.45) NLINE = 0
101     WRITE(6,3) ASTAR,H0,RHOO,S0,RHOF1,T1,H1,U1,URHO,GAMBAR
102     GO TO 140
103     C
104     C          PART 2 OUTPUT
105     C
106     40 CONTINUE
107     IF(IL.NE.0) GO TO 50
108     C
109     C          STANDARD OUTPUT
110     C
111     WRITE(6,4) U2,RHO2,CAPJ2,T2,P2,RSTAR2,SIG2
112     GO TO 140
113     50 CONTINUE
114     IF(IL.NE.1) GO TO 60
115     C
116     C          EXTENDED OUTPUT - 1
117     C
118     IF(NENTRY.EQ.1.OR.NLINE.EQ.0) WRITE(6,5)
119     IF(NENTRY.LT.N2) IFLG = 2
120     IF(NLINE.EQ.0) WRITE(6,6)
121     IF(NLINE.EQ.0.AND.IFLG.EQ.2) WRITE(6,7)
122     IF(NLINE.EQ.0) NLINE = NLINE + 6
123     IF(NLINE.EQ.6.AND.IFLG.EQ.2) NLINE = NLINE + 1
124     NLINE = NLINE + 1
125     IF(NLINE.GT.45.AND.IFLG.EQ.1) NLINE = 0
126     XTT = T2W/T0
127     PP = P/P0
128     WRITE(6,3) XTT,H2W,U2W,RHO,PP,PINF,PBAR,X2,GAMBAR
129     N2 = NENTRY
130     GO TO 140
131     60 CONTINUE
132     C
133     C          EXTENDED OUTPUT - 2
134     C
135     NLINE = NLINE + 1
136     IF(NLINE.GT.45) NLINE = 0
137     WRITE(6,3) TR,SIGMAX,RSTAR,CAPL,PHI,J
138     GO TO 140
139     C
140     C          PART3 OUTPUT
141     C
142     70 CONTINUE
143     IF(IL.NE.0) GO TO 120
144     C
145     C          STANDARD OUTPUT
146     C
147     WRITE(6,8)
148     NLINE = 6
149     J3M1 = J3 - 1
150     DO 80 I=1,J3M1
151     IF(NLINE.EQ.0) WRITE(6,8)
152     IF(NLINE.EQ.0) NLINE = NLINE + 6
153     NLINE = NLINE + 1
154     IF(NLINE.GT.45) NLINE = 0
155     PP = P3(I)/P0
156     TT = T3(I)/T0
157     WRITE(6,3) X3(I),PP,TT,CAPJX3(I),CAPJY3(I),DELN3(I),U3(I),YS3(I)
158     1 ,DELS3(I)
159     80 CONTINUE
160     IF(IL.NE.100) GO TO 120
161     REWIND 7
162     WRITE(6,11)
163     90 CONTINUE
164     READ(7,END=100) JJJ,(R3(I),MU3(I),HLI3(I),SLI3(I),TL3(I),YIJ3(I)
165     1 ,I=1,JJJ)
166     100 IF(EOF(7).NE.0) GO TO 140

```

```

167      WRITE(6,12) JJJ,X3(JJJ),T3(JJJ)
168      DO 110 I=1,JJJ
169      WRITE(6,13) I,R3(I),MU3(I),HLI3(I),SLI3(I),TL3(I),YIJ3(I)
170 110 CONTINUE
171      GO TO 90
172 120 CONTINUE
173 C
174 C      DEBUG OUTPUT
175 C
176      IF(IL.NE.1) GO TO 130
177      IF(J3.EQ.1) NLINE = 0
178      IF(NLINE.EQ.0) WRITE(6,9)
179      IF(NLINE.EQ.0) WRITE(6,15)
180      IF(NLINE.EQ.0) WRITE(6,16)
181      IF(NLINE.EQ.0) NLINE = NLINE + 9 + (J3+1)/9
182      WRITE(6,10) J3,T3(J3+1),P3(J3+1),U3(J3+1),YS3(J3+1),S3(J3+1),
183      1 SL3(J3+1),HL3(J3+1),X3(J3+1),A3(J3+1)
184      WRITE(6,17) RH03(J3+1),RSTAR3(J3+1),DELY3(J3),DELN3(J3),
185      1 TS3(J3+1),CP1,GAMBAR
186      WRITE(6,14) (R3(IJKL),IJKL=1,J3)
187      NLINE = NLINE + 3 + (J3+1)/9
188      IF(NLINE.GT.45) NLINE = 0
189      GO TO 140
190 130 CONTINUE
191 140 CONTINUE
192      RETURN
193      END

```

```

1      SUBROUTINE SATTEM(TS,PX)
2 C
3      SUBROUTINE SATTEM CALCULATES THE SATURATION TEMPERATURE
4 C
5      COMMON/SIGCOM/SIGMA(10),SIG,PSUPO
6      COMMON/ADJUST/GAMPA1,QC,ALPHA,BETA,DSTAR,ASTAR,DT2,
7      1 JMIN,DELX,EPS(8),IOUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
8      REAL JMIN
9 C
10 C
11 C      SOLVE EQUATION (57) FOR T
12 C
13      TOLD = 300.
14      ALOP = ALOG(PX*SIGMA(1)/SIG)
15 10 CONTINUE
16      F = 55.897 - 6641.7/TOLD - 4.4864*ALOG(TOLD) - ALOP
17      FP = 6641.7/TOLD**2 - 4.4864/TOLD
18      TNEW = TOLD - F/FP
19      IF(ABS(TNEW-TOLD)/TOLD.LT.EPS(1)) GO TO 20
20      TOLD = TNEW
21      GO TO 10
22 20 CONTINUE
23      TS = TNEW
24      RETURN
25      END

```

```

1      SUBROUTINE XYSA(ALST,XLST)
2
3      C      SUBROUTINE XYSA CALCULATES THE X POSITION IN THE
4      C      NOZZLE AS A FUNCTION OF AREA
5      C      ACOEF CONTAINS THE SPLINE COEFFICIENTS DETERMINED
6      C      BY THE LIBRARY ROUTINE CSDS
7
8      COMMON/ARECOM/NA,XA,ACDEF
9      DIMENSION ACOEF(10,4)
10     DIMENSION A(10)
11     COMMON/CONST/TC,K,CAPR,M1,W(10),RHOL,RBAR,PI,ALPHAC
12     REAL K,M1
13     COMMON/ADJUST/GAMMA1,QC,ALPHA,BETA,DSTAR,ASTAR,DT2,
14     1 JMIN,DELX,EPS(8),IDUT,DT1,CVRAT,ARAT,JSTOP,JDB,CP,CP1
15     REAL JMIN
16     DIMENSION XA(10)
17
18     C      DO 10 I=1,NA
19     A(I) = ACOEF(I,1)
20     A(I) = PI*A(I)**2
21     10 CONTINUE
22     AREA = ALST
23     RBARX = SQRT(AREA/PI)
24     NPD = NA-1
25     DO 20 IJ=1,NPD
26     IF(AREA.GE.A(IJ).AND.AREA.LE.A(IJ+1)) GO TO 30
27     20 CONTINUE
28     IJ = NPD
29     30 CONTINUE
30     HOLD = 0.5*(XA(IJ+1) - XA(IJ))
31     40 CONTINUE
32     FXX = ((ACDEF(IJ,4)*HOLD + ACOEF(IJ,3))*HOLD
33     1 + ACOEF(IJ,2))*HOLD + ACOEF(IJ,1)
34     FXX = FXX - RBARX
35     FXXP = (3.*ACDEF(IJ,4)*HOLD + 2.*ACDEF(IJ,3))*HOLD
36     1 + ACOEF(IJ,2)
37     HNEW = HOLD - FXX/FXXP
38     IF(ABS(HNEW-HOLD)/HOLD.LT.EPS(8)) GO TO 50
39     HOLD = HNEW
40     GO TO 40
41     50 CONTINUE
42     XLST = XA(IJ) + HNEW
43     IF(AREA.LT.A(1)) XLST = (AREA/A(1))*XA(1)
44     RETURN
45     END

```

References

1. Hill, Philip G.: Condensation of Water Vapor During Supersonic Expansion in Nozzles. *J. Fluid Mech.*, vol. 25, pt. 3, July 1966, pp. 593-620.
2. Gyarmathy, G.: *Condensation in Flowing Steam. Two-Phase Steam Flow in Turbines and Separators*, M. J. Moore and C. H. Sieverding, eds., Hemisphere Publ. Corp., c.1976, pp. 127-189.
3. Young, J. B.: *Spontaneous Condensation of Steam in Supersonic Nozzles*. Dep. of Engineering, Univ. of Cambridge, 1980.
Part I—Nucleation and Droplet Growth Theory. CUED/A-Turbo/TR 97, Pt. I.
Part II—Numerical Methods and Comparison With Experimental Results. CUED/A-Turbo/TR 97, Pt. II.
4. Young, J. B.: The Spontaneous Condensation of Steam in Supersonic Nozzles. *PhysicoChem. Hydrodyn.*, vol. 3, no. 1, 1982, pp. 57-82.
5. Keenan, Joseph H.; Keyes, Frederick G.; Hill, Philip G.; and Moore, Joan G.: *Steam Tables—Thermodynamic Properties of Water Including Vapor, Liquid, and Solid Phases*. John Wiley & Sons, Inc., c.1978.
6. Kantrowitz, Arthur: Nucleation in Very Rapid Vapor Expansions. *J. Chem. Phys.*, vol. 19, no. 9, Sept. 1951, pp. 1097-1100.
7. Touloukian, Y. S.; Saxena, S. C.; and Hestermans, P.: *Viscosity. Thermophysical Properties of Matter, Volume II*, IFI/Plenum, c.1975.
8. Touloukian, Y. S.; Liley, P. E.; and Saxena, S. C.: *Thermal Conductivity—Nonmetallic Liquids and Gases. Thermophysical Properties of Matter, Volume 3*, IFI/Plenum, 1970.
9. Anderson, E. C.; and Lewis, C. H.: *Laminar or Turbulent Boundary-Layer Flows of Perfect Gases or Reacting Gas Mixtures in Chemical Equilibrium*. NASA CR-1893, 1971.
10. *JANAF Thermochemical Tables*. Thermal Lab., Dow Chemical Co., June 30, 1965.

Table 1. Conditions for Numerical Results

[For all cases: $q_c = 1$, $\alpha = 8$, $\alpha_c = 1$, $\beta = 2$, and $J_{\min} = 10^{15}$]

Case	T_o , K	p_o , bars	ϕ	y_{H_2O}
1	1900	50	0.798	0.154
2	1900	250	.797	.154
3	1600	50	.620	.122
4	1600	250	.620	.122
5	1900	250	.427	.156

Table 2. Nozzle Coordinates for Langley 8'HTT and Computed
Boundary-Layer-Displacement Thickness

x, m	r_w, m	δ^*, m , for—			
		Case 1	Cases 2 and 5	Case 3	Case 4
0	0.0710	0	0	0	0
.0860	.0714	0	0	0	0
2.5400	.3538	.0072	.0059	.0073	.0060
5.4703	.6911	.0271	.0213	.0275	.0217
6.4230	.7938	.0358	.0281	.0363	.0286
9.8560	1.0434	.0670	.0523	.0675	.0528
12.8949	1.1660	.0911	.0713	.0916	.0718
15.7116	1.2192	.1089	.0851	.1093	.0855

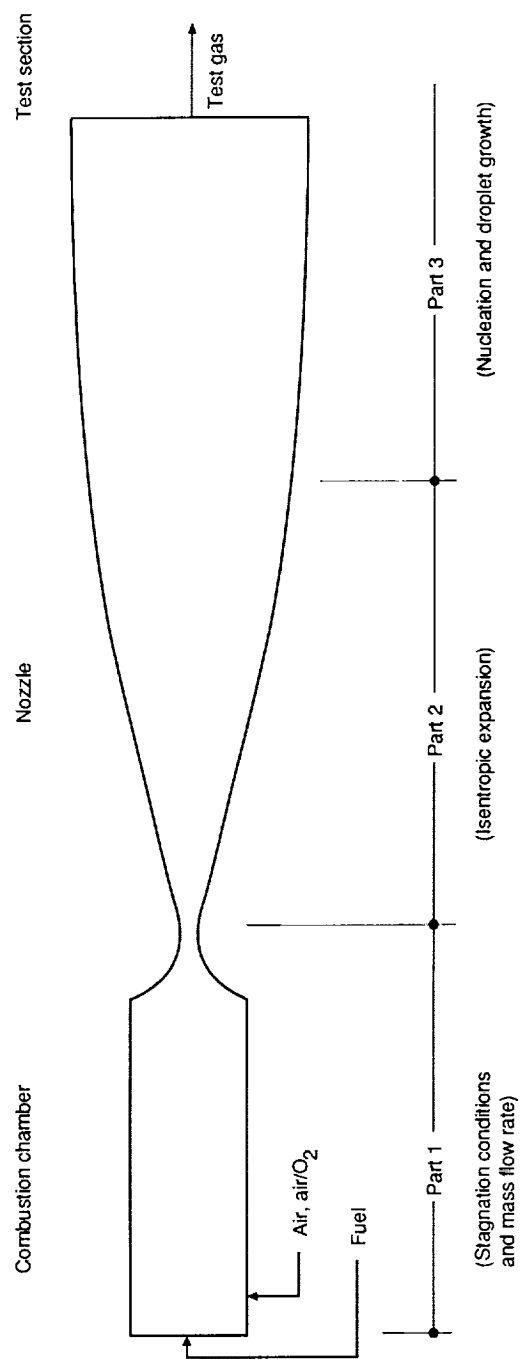
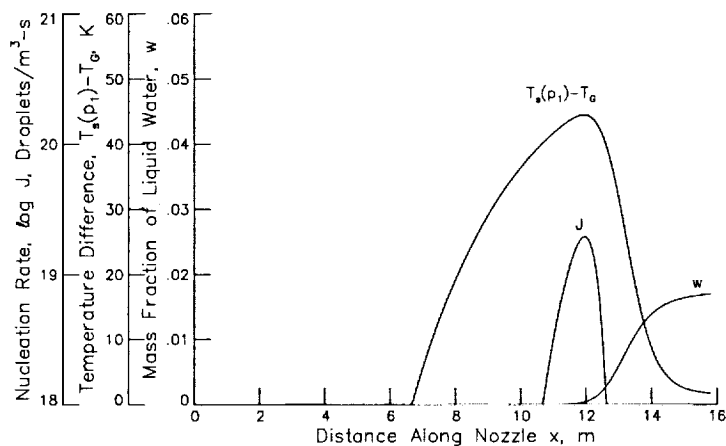
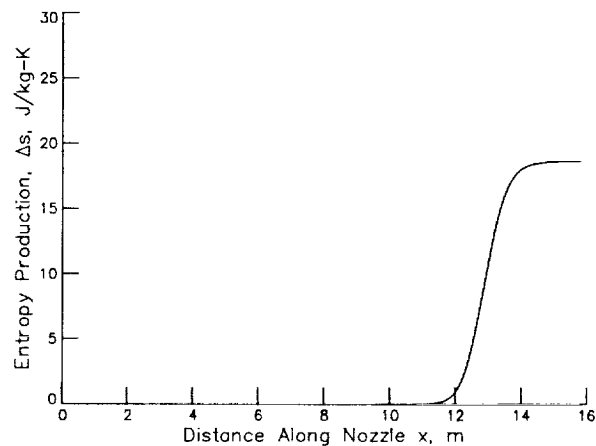


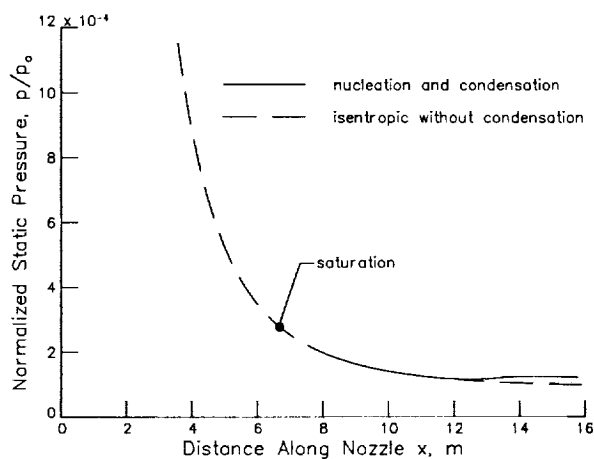
Figure 1. Schematic of combustion-heated wind tunnel.



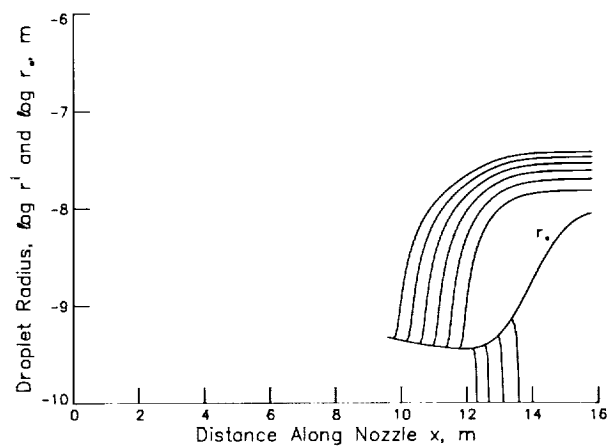
(a) Temperature difference, nucleation rate, and mass fraction liquid water.



(b) Entropy production.

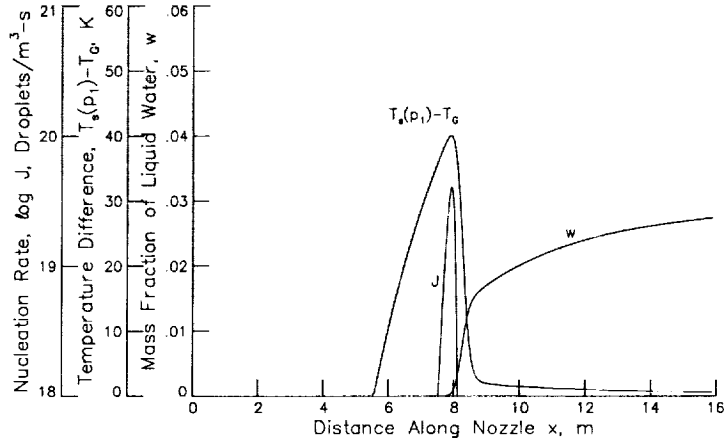


(c) Static pressure distribution.

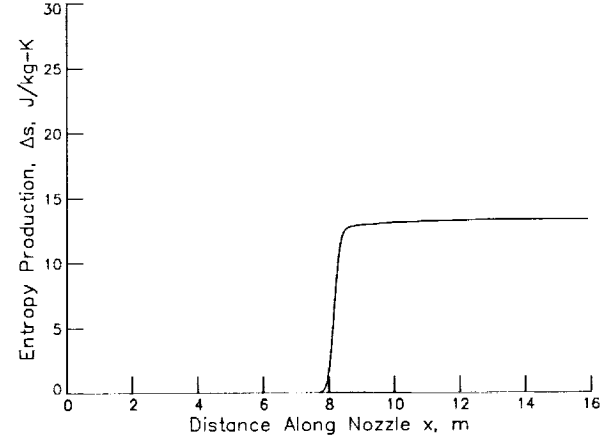


(d) Droplet growth.

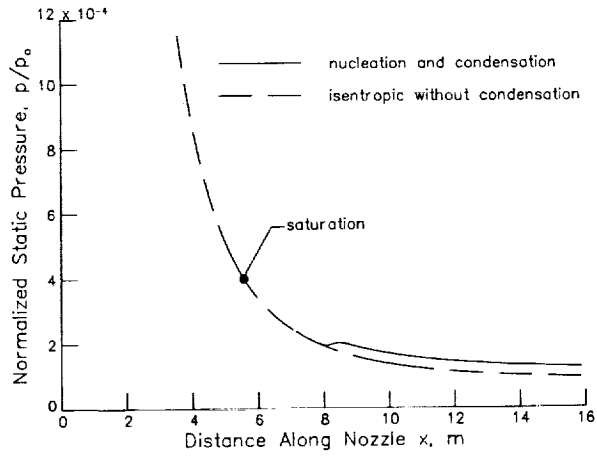
Figure 2. Numerical results for case 1 with $T_0 = 1900$ K, $p_0 = 50$ bars, and $\phi = 0.798$.



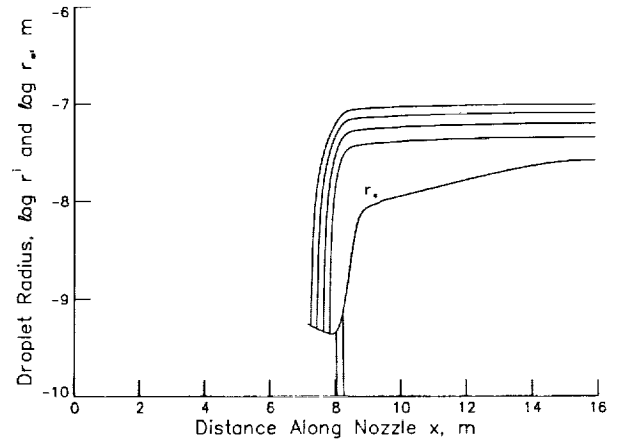
(a) Temperature difference, nucleation rate, and mass fraction liquid water.



(b) Entropy production.

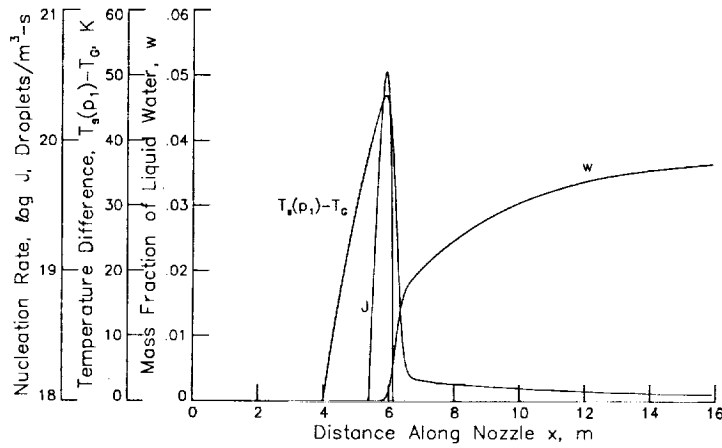


(c) Static pressure distribution.

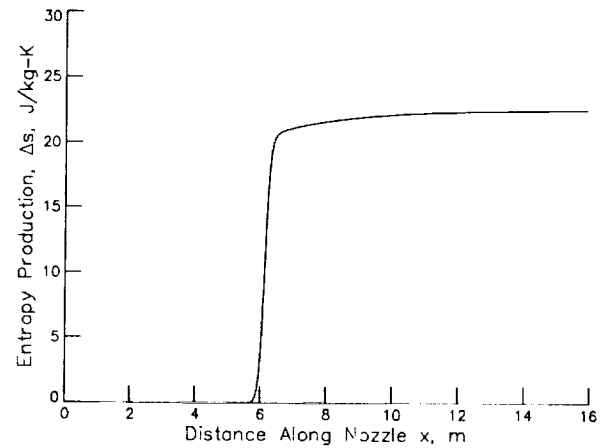


(d) Droplet growth.

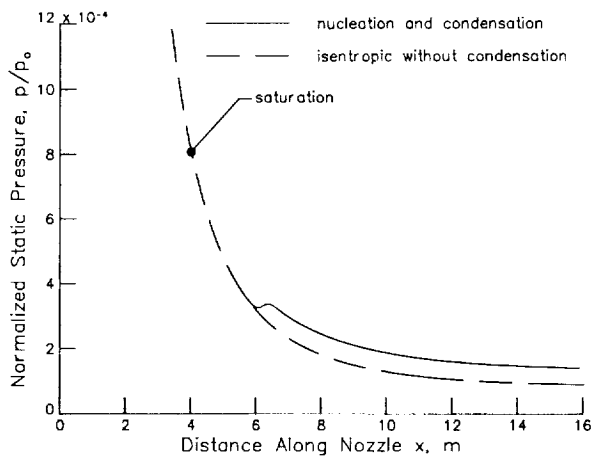
Figure 3. Numerical results for case 2 with $T_0 = 1900$ K, $p_0 = 250$ bars, and $\phi = 0.797$.



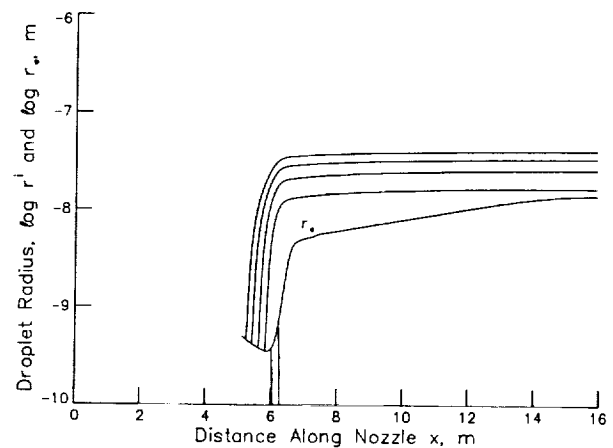
(a) Temperature difference, nucleation rate, and mass fraction liquid water.



(b) Entropy production.

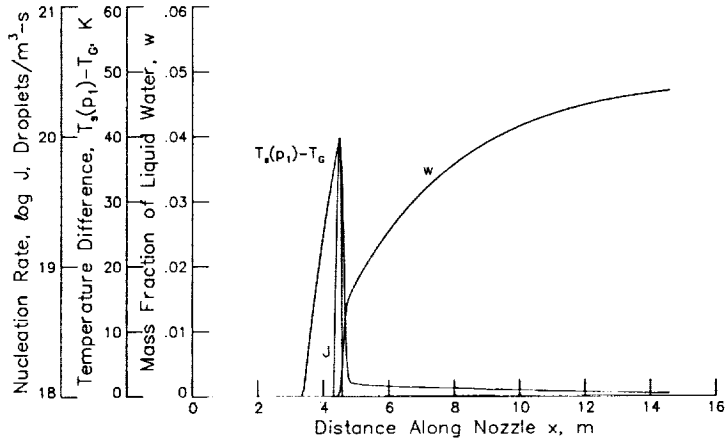


(c) Static pressure distribution.

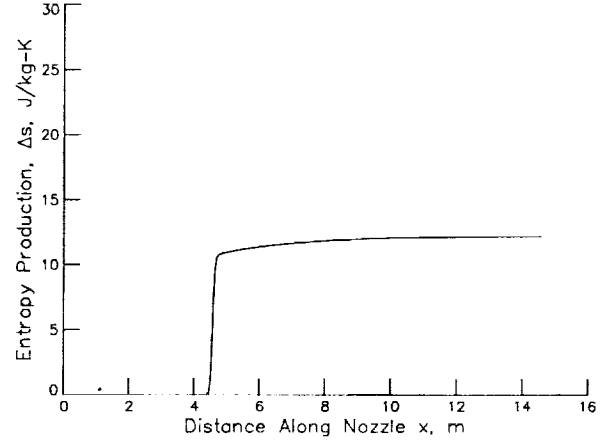


(d) Droplet growth.

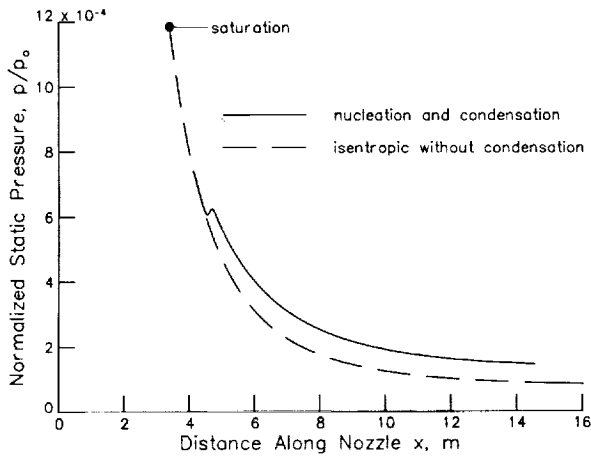
Figure 4. Numerical results for case 3 with $T_0 = 1600$ K, $p_0 = 50$ bars, and $\phi = 0.620$.



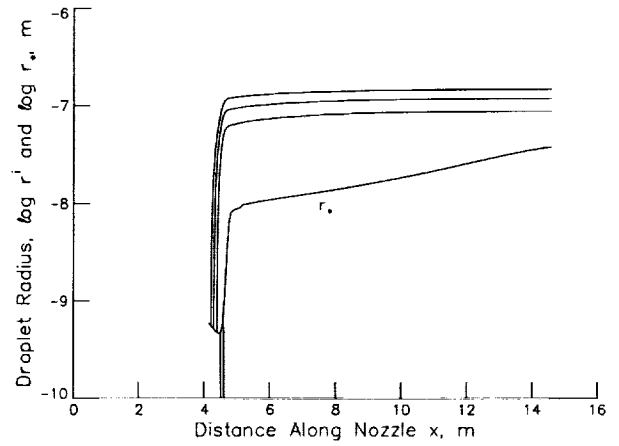
(a) Temperature difference, nucleation rate, and mass fraction liquid water.



(b) Entropy production.

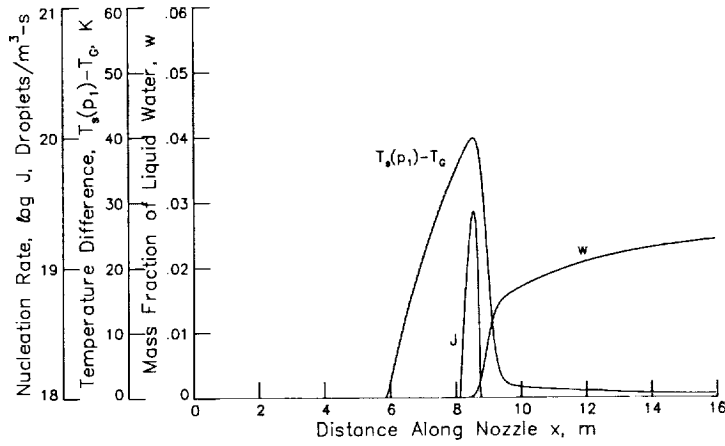


(c) Static pressure distribution.

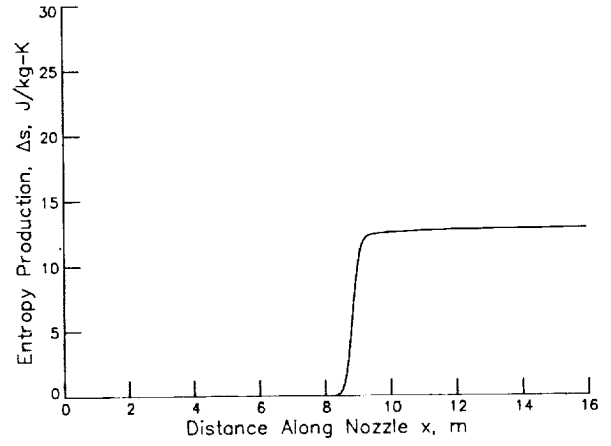


(d) Droplet growth.

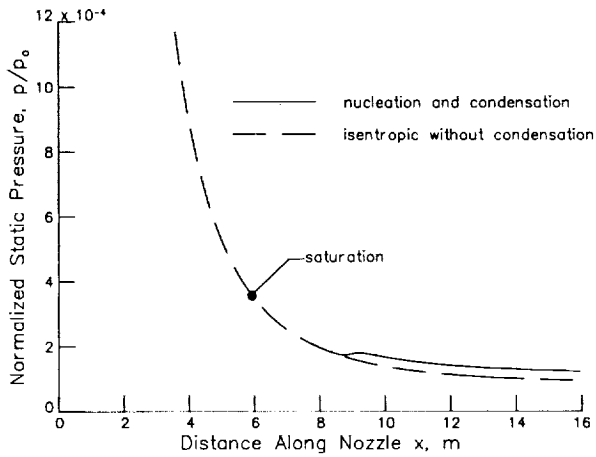
Figure 5. Numerical results for case 4 with $T_o = 1600$ K, $p_o = 250$ bars, and $\phi = 0.620$.



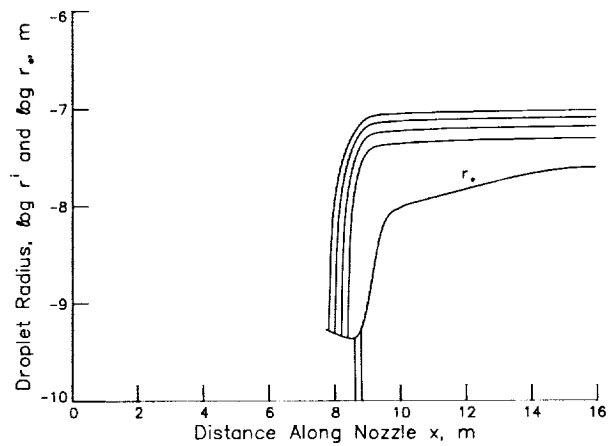
(a) Temperature difference, nucleation rate, and mass fraction liquid water.



(b) Entropy production.



(c) Static pressure distribution.



(d) Droplet growth.

Figure 6. Numerical results for case 5 with $T_0 = 1900$ K, $p_0 = 250$ bars, and $\phi = 0.427$.

Report Documentation Page

1. Report No. NASA TP-2833	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Finite-Rate Water Condensation in Combustion-Heated Wind Tunnels		5. Report Date September 1988	
		6. Performing Organization Code	
7. Author(s) Wayne D. Erickson, Gerald H. Mall, and Ramadas K. Prabhu		8. Performing Organization Report No. L-16443	
		10. Work Unit No. 505-62-31-01	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Paper	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		14. Sponsoring Agency Code	
15. Supplementary Notes Wayne D. Erickson: Langley Research Center, Hampton, Virginia. Gerald H. Mall: Computer Sciences Corporation, Hampton, Virginia. Ramadas K. Prabhu: PRC Systems Services, A Division of Planning Research Corporation, Hampton, Virginia.			
16. Abstract A quasi-one-dimensional method for computing finite-rate nucleation and droplet growth of water in a supersonic expansion of combustion products is presented. Sample computations are included for the Langley 8-Foot High-Temperature Tunnel, but the method can also be applied to other combustion-heated wind tunnels. The sample results indicate that the free-stream static pressure can be in the range of 25 to 60 percent greater than that computed for isentropic nozzle flow without water condensation. The method provides a tool for examining the effects of water condensation on static state properties and velocity of the supersonic stream in combustion-heated wind tunnels.			
17. Key Words (Suggested by Author(s)) Combustion-heated wind tunnels Finite-rate water condensation Nucleation Droplet growth		18. Distribution Statement Unclassified—Unlimited	
		Subject Category 09	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 74	22. Price A04